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Water activity measurement of NaCl/H₂O mixtures via substrate-integrated hollow waveguide infrared spectroscopy with integrated microfluidics

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ABSTRACT

A microfluidic system combined with substrate-integrated hollow waveguide (iHWG) vapor phase infrared spectroscopy has been developed for evaluating the chemical activity of volatile compounds dissolved in complex fluids. Chemical activity is an important yet rarely exploited parameter in process analysis and control. The instrumental approach developed herein uniquely enables controlled evaporation/permeation from a sample solution into a hollow waveguide structure, and analyzing the partial pressures of volatile constituents. It was shown that the chemical activity may be deduced from partial pressure measurements at thermodynamic equilibrium conditions. The combined microfluidic-iHWG mid-infrared sensor system allows realizing such studies in absence of any perturbations provoked by sampling operations. In this study, the first water activity measurement made by a microfluidic-iHWG device is presented. For proof-of-concept purpose water-NaCl mixtures are investigated.

Keywords: chemical activity, sensor, microfluidic, FTIR spectroscopy, iHWG

INTRODUCTION

Industrial processes increasingly rely on complex fluid handling. However, detailed understanding on such fluid behavior frequently remains empirical due to their many constituents. In order to improve mechanistic understanding, new multiscale simulation packages are required. The latter development is especially difficult at mesoscale dimensions, since molecule aggregation, interface structures and system behavior are yet to be fully understood in most cases. However, a signature of aggregation can be found within solvent activity variations. Activity therefore becomes an important parameter, which advanced modelling packages are required to simulate [1,2]. Hence, there is a definite need to reliably measure and analyze chemical activity for each volatile component in such complex mixtures. To achieve this goal, the most straightforward approach is to measure

partial pressures of all chemicals, and to follow their changes as a function of time and concentration.

Surprisingly, to the best of our knowledge, following chemical activities to study complex fluid behavior has yet to be performed and exploited routinely and in real-time. We attribute the lack of reports on this highly relevant aspect to the technical difficulties of the associated experimental setup. Yet, such analyses would be a major breakthrough in advancing fundamental understanding and modelling of these fluids, as well as real-time process monitoring [3]. In particular, chemical processes associated with any separation plant, controlled crystallization reactors, or purification/recycling systems such as complex alcohol pertraction for “rectification” in distilleries, alcohol aggregation [4] or water activity to track monoclonal antibody agglomeration (a \$141 bn market in 2017) would benefit from such capabilities.

Direct and (near) real-time measurement of chemical activity of volatile components remains challenging, however, may be derived from the measurement of equilibrium partial pressures according to Raoult’s law. Notwithstanding, the partial pressures are correlated to the infrared absorbance of vapor phase constituents in equilibrium with the liquid sample [5]. Here, Fourier transform infrared spectroscopy (FTIR) is used as a fast and nondestructive method enabling simultaneous detection of several vapor phase species based on their roto-vibrational absorptions. However, gas cell assemblies (e.g., White cells or Herriott cells) are normally bulky and require sizeable sample volumes up to a few liters, thereby considerably increasing equilibrium times and limiting their use for transient or real-time experiments [6,7].

In the present study, we report an innovative approach for chemical activity measurements by integrating a microfluidic cartridge and a liquid-vapor sampling cell based on iHWG technology [8,9] for rapid equilibration. Because of air moisture it is not straightforward to perform FTIR measurements of water bands. This study reports water activity measurements of water-NaCl mixtures performed with the device and compared them to literature values.

MATERIALS AND METHODS

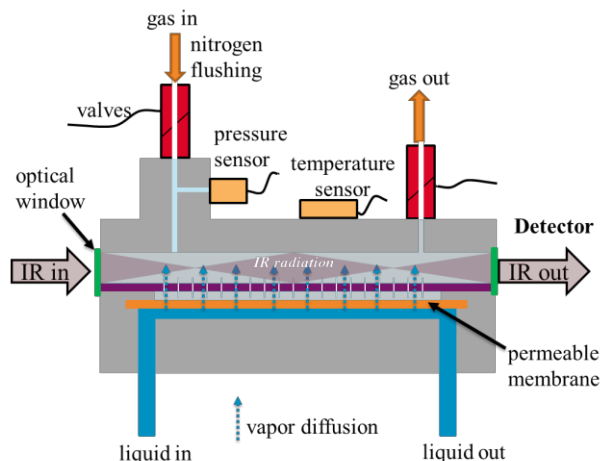


Figure 1: Schematic cross-section of the experimental setup (not drawn to scale)

A schematic cross-section of the sandwiched microfluidic card and iHWG device used in this study is shown in Figure 1. Measurement began by injecting the liquid sample into the microfluidic channel located on the bottom part (blue). Volatile molecules could then evaporate from the liquid sample through a permeable membrane (orange), and subsequently diffuse (blue dotted arrows) to the iHWG through small perforations (purple). Infrared radiation emitted from an FTIR spectrometer (MIR, 2–20 μm , red) is coupled into the iHWG through optical windows (green). Inside the waveguide the infrared beam probes vapor molecules; the output intensity I is measured via a detector. Absorbance spectra A are derived by ratioing the reference intensity I_0 recorded in the absence of absorbing species to the sample intensity I (equation 1).

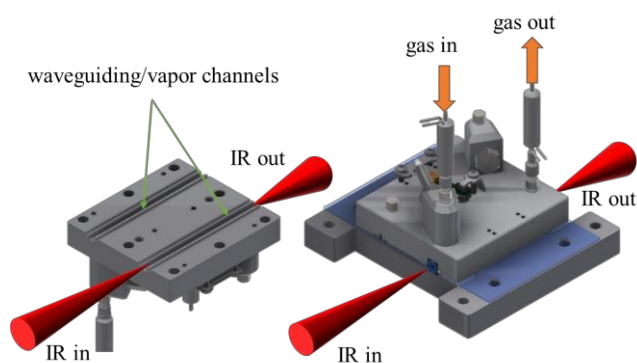


Figure 2: Left: iHWG part with two vapor channels, Right: microfluidic/iHWG assembly. Purging gas is controlled by two solenoid valves.

$$A = 10 \log_{10} \left(\frac{I_0}{I} \right) \quad (1)$$

The reference single-channel spectrum I_0 is measured by opening the two solenoid valves on top the iHWG, i.e., whilst nitrogen is flushing. Although evaporation through the membrane continues naturally, using a sufficiently high N_2 flow rate ensures that all analyte concentrations inside the waveguide are kept at negligible levels throughout the reference spectra acquisition.

Absorbance spectra enable the quantification of vapor molecules in thermodynamic equilibrium with the liquid phase. This quantitative information is then transferred to thermodynamic activity thanks to Raoult's law. A detailed description of the device fabrication and theory is provided by Kokoric et al. [5].

It should be indicated that the assembly described in this study actually comprised two iHWG channels, although only one channel was used for measurement.

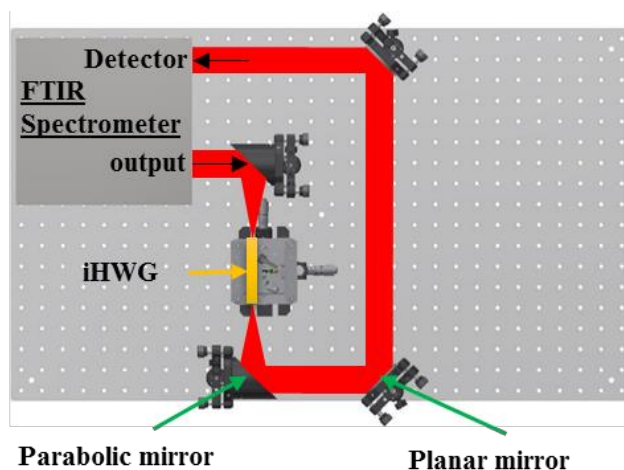


Figure 3: Top view of the experimental setup, IR beam path represented in red

The microfluidic IR-iHWG assembly was optically coupled to the FTIR spectrometer (Bruker Alpha OEM, Bruker Optics Inc., Ettlingen, Germany) using an off-axis parabolic mirror (OAPM) (MPD229-M01, Thorlabs GmbH, Dachau/Munich, Germany) with a focal length of 2". After propagating through the iHWG channel, IR radiation emanating at the distal end was guided to an internal DTGS detector by a second OAPM mirror and two planar mirrors (PF20-03-M01, Thorlabs GmbH, Dachau/Munich, Germany) (Figure 3). All IR spectra were recorded in the spectral window of 4500 to 750 cm^{-1} at a spectral resolution of 2 cm^{-1} . To keep the temperature constant, the entire experiment was placed inside a temperature controlled chamber (IPP750 plus, Memmert, Germany). In the present study, a constant temperature of $25^\circ\text{C} \pm 0.1^\circ\text{C}$ was maintained. In addition the temperature controlled chamber was continuously flushed with nitrogen to remove air moisture from the IR beam path. A syringe pump (New Era NE1010, New Era Pump Systems Inc., USA) provides a

constant sample flow of 50 $\mu\text{L}/\text{min}$. Mixtures of NaCl/water were prepared by diluting NaCl salt with MilliQ water. As reported in the following, mixtures of 0, 100, 200 and 300 g/L NaCl were measured. For this purpose, different liquid mixtures were injected into the microfluidic channel via the syringe pump prior to initiating the vapor phase IR measurements.

MEASUREMENTS OF NaCl/WATER SOLUTIONS

A protocol was developed for the measurement of different NaCl-water mixtures: First, 2 mL of the liquid sample are injected inside the channel, thereby flushing the previous sample. Then, the iHWG channel is purged with nitrogen at a constant flow for 5 min, thus ensuring complete gas exchange with nitrogen. Whilst purging the iHWG continues, a reference spectrum is recorded, yet, with sample already present within the microfluidic channel. Four control absorbance spectra are then recorded. Finally, the purging gas stream is turned off and IR measurements of sample vapors are initiated while perfusing the sample at a flow rate of 50 $\mu\text{L}/\text{min}$. Pure water measurements were repeated five times, and of each NaCl mixture three times.

DATA EVALUATION

Recorded absorbance spectra show several peaks due to water molecule absorptions. Corresponding peaks were integrated using integration boundaries from 3900-3600 cm^{-1} and 1875-1350 cm^{-1} . Figure 5 shows the integrals as a function of time and salt concentration. In general, the water peak integrals increase, and finally reach a plateau. On the other hand, the plateau values decrease with increasing salt concentration.

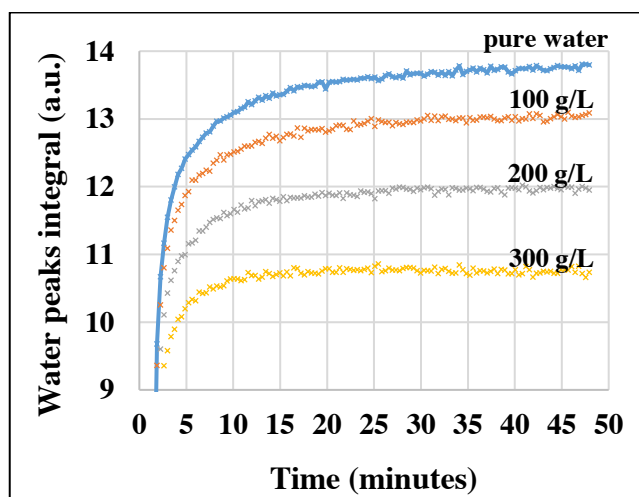


Figure 4: Water peak integrals as a function of time and NaCl concentration at 25°C

Figure 5 shows a plot of the water activity as a function of NaCl molarity. The correlation between absorbance and activity of the investigated NaCl solutions was obtained by dividing the water integrals of the mixtures by the pure water

integral (equation 2). A physiochemical explanation of the link between FTIR absorbance A and activity a is given in our previous publication [5].

$$a_{\text{water}}(x_{\text{mix}}) = \frac{A_{\text{mix}}}{A_{\text{water}}} \quad (2)$$

$$U(a_i) = 2 \sqrt{a_i^2 \left(\frac{\sigma_{\text{mix}}^2}{A_{\text{mix}}^2} + \frac{\sigma_{\text{water}}^2}{A_{\text{water}}^2} \right)} \quad (3)$$

For calculations, the average value of the last twenty points of each measurement, where thermodynamic equilibrium is reached, is used. Hence, integrated absorbance averages for each concentration i as well as for pure water are calculated together with their related standard deviation σ_i . Thus a calculation of the expanded uncertainty U (equation 3) from a_{water} formula (equation 2) is enabled. A coverage factor of 2 is taken giving a 95.4% confidence level [10].

RESULTS

As expected, the water activity decreases with increasing NaCl salt concentration. Those results are in good agreement with established literature values like those given by Robinson and Stokes in 1959 [11].

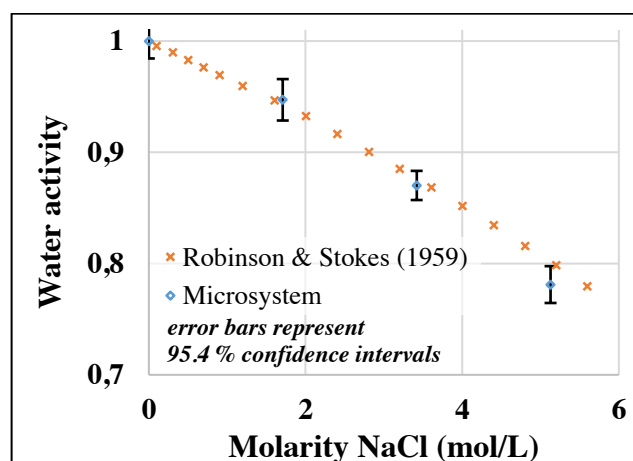


Figure 5: Water activity as a function of NaCl concentration at 25°C; values measured by the iHWG-microfluidic device compared to literature values.

DISCUSSION

This work presents the first measurement of water activity using a microfluidic IR-iHWG assembly combined with FTIR spectroscopy. Such measurements are particularly challenging due to the short active optical path, when compared to the overall one (e.g., White cells or Herriott cells). Hence, it is of utmost importance to avoid any parasitic (atmospheric) water vapor within the remaining optical path. Under such precautions, a good agreement with literature data can be obtained, thus enabling sound water activity measurements with the iHWG-microfluidic device. In a previous study, the measurement of ethanol activity in ethanol-water mixtures was presented [5], which – combined

with the present study – opens the way to multi-solvent mixture investigations, for example ethanol and water, which can both be followed simultaneously. The use of FTIR makes this approach much more versatile than other gas detection techniques such as nonosensors [12,13], as the only requirements for following gas mixtures are (i) that they have a sufficiently strong infrared signature and (ii) that the gases respective peaks are either well separated or that they can be deconvoluted. Thus, a new step in the study of the thermodynamics of complex fluid study is reached. Fast and easy measurement of solvent activities should enable a better understanding and simulation of complex fluids in different domains including extraction, refining, distillation, or agglomeration.

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The manuscript was written through contributions from all authors. ‡ These authors contributed equally.

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