Laser-based Quantification of Heat and Mass Transfer across the Phase Boundaries of Droplets during Mixing in the Supercritical Antisolvent Process

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The mass transfer across the phase boundaries of the liquid solvent injected into supercritical CO_2 at so called subcritical conditions of the SAS process is studied by inelastic laser light scattering. Intense calibration measurements were carried out and qualified Raman spectroscopy for quantitative investigations in such high pressure systems. Hanging droplets of ethanol in supercritical CO_2 are produced under steady state conditions to measure the composition spatially resolved along a line near the phase boundary. The two mass transfer phenomena occurring, which are evaporation of the liquid phase and absorption of the gas phase into the liquid phase, can be decoupled by slight changes in the experimental procedure.

INTRODUCTION

The supercritical antisolvent (SAS) process is a seminal technology to produce particles for many medical, pharmaceutical, or engineering applications [1]. In this process, a solution of organic solvent and solute is injected into a vessel of supercritical antisolvent. Solvent, antisolvent, and solute are chosen in a way, that solvent and antisolvent have a high miscibility, while the solute is not miscible in the ternary mixture of the three components. By this means, the mixing of the three components after the injection leads to a supersaturation of the solute in the ternary mixture and therefore a growth of particles, which are finally the product of the SAS process. Mostly supercritical CO_2 is used as antisolvent due to its moderate critical parameters of 304 K and 7.4 MPa. This qualifies CO_2 for the particle production of heat-sensitive or pressure-sensitive materials as pharmaceuticals, dyes, or semiconductor materials [2]. The produced particles are filtered on a grid in the vessel, and solvent and antisolvent split in liquid and gas phase after expansion and can be recycled.

By changing the process parameters as pressure, temperature, initial solute concentration or flow rates, the morphology of the produced particles can be affected. For different locations in the fluid phase equilibrium diagram, particles in the nanometer range, hollow microspheres or microparticles can be obtained [3]. A special reference point separating the different particle morphologies is the critical pressure of the mixture (MCP = mixture critical point) of organic solvent and antisolvent CO_2, which is a function of temperature (see Figure 1). At so-called subcritical operating conditions, where the pressure is above the critical pressure of pure CO_2, but below the MCP for the adjusted operation temperature, the injected solvent disperses into droplets during the injection into the supercritical CO_2. In this case, the mass transfer across the phase boundary between the liquid solvent and the supercritical antisolvent has an influence on the mixing of these two components and therefore on the particles, that will be obtained. In this study, hanging drops of liquid solvent in supercritical CO_2 were produced [4] and calibration measurements to investigate the mass transfer by detecting the composition in

the vicinity of the droplet along a line by means Raman spectroscopy were carried out successfully. The measurement technique was already applied in a different phase boundary mass transfer problem [5].
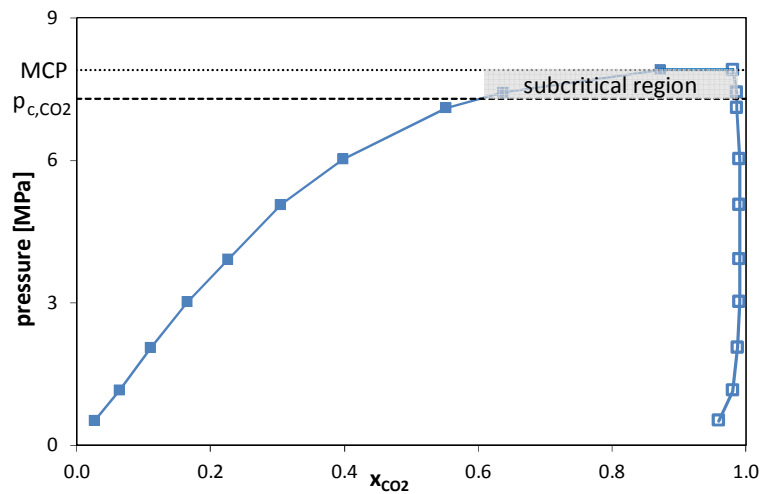

Figure 1: Fluid phase equilibrium diagram of EtOH/CO_2 at 313 K [6]

MATERIALS AND METHODS

Ethanol was delivered by Merck with a purity of 99.9 % and CO_2 was delivered by Linde with a purity of 99.9 %. Both fluids were brought in the measurement chamber by syringe pumps, whereat CO_2 was cooled to 273 K and liquefied to control the mass flow rate. The high pressure chamber had an internal volume of approximately 100 ml and was equipped with three windows to carry out the optical measurements. Four electrical heating cartridges and a backpressure regulator enable to adjust pressure and temperature inside the chamber.

Raman spectroscopy is a laser measurement technique based on inelastic light scattering, which can be realized for several measurement volume geometries [7-9]. In contrast to elastic light scattering processes, e.g. Rayleigh scattering, the scattering molecule changes its energy level during the interaction with the laser photon. Due to energy conservation, the energy difference between the exciting and the scattered photon is the energy difference between the molecular energy levels occupied before and after the scattering process of the involved molecule. This energy difference is often called Raman shift, given in wavenumbers (cm^{-1}), and has a certain value for different kind of molecules. As the intensity of the Raman scattered light is (mostly) directly proportional to the number of scattering molecules, Raman spectroscopy is a quantitative and species sensitive measurement technique, which qualifies for composition measurements. Figure 2 shows Raman spectra of pure ethanol (293 K, 0.1 MPa), pure CO_2 (297 K, 6.9 MPa) and a liquid mixture ($x_{CO2} = 0.5$, 297 K, 6 MPa). CO_2 has two narrow peaks at 1285 cm^{-1} and 1388 cm^{-1}. Ethanol has a significant peak from the CH-bond at 2928 cm^{-1} and a broad band from the OH-bond between 3100 cm^{-1} and 3700 cm^{-1}. Furthermore, it shows several smaller peaks in the so called fingerprint region between 800 cm^{-1} and 1600 cm^{-1}. It can be seen, that the spectrum of the mixture is, with respect to the different densities, a superposition of the spectra of the pure components. One drawback of Raman measurement techniques are the low scattering cross section and therefore the weak signal, which is compensated in high pressure systems by the large number of molecules contributing to the signal intensity. It is a non-invasive technique which can

provide a high spatial resolution. Therefore, Raman scattering has already been applied successfully to study the particle formation in the SAS process [10] and is also the method of choice to measure concentration for the investigation of the mass transfer in this study. If components forming hydrogen bonds, e.g. ethanol, are present in the mixture, it is also possible to derive the temperature from the shape of the OH-bond signal in the Raman spectrum [5].
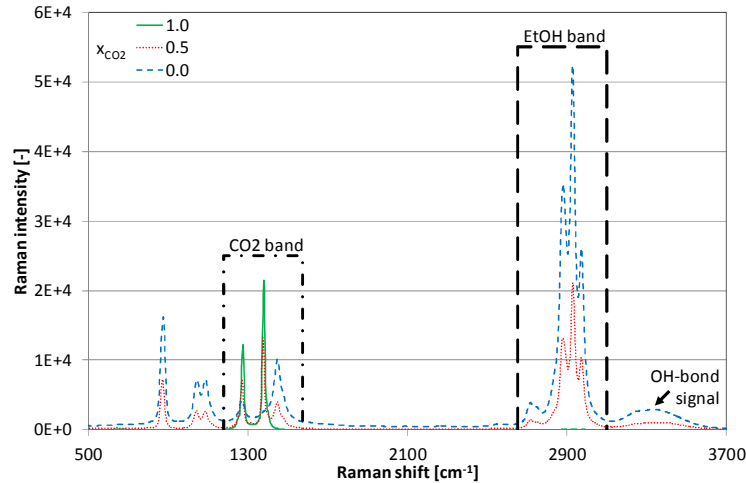

Figure 2: Raman spectra of CO_2, ethanol, and a mixture

The apparatus to generate pendant droplets of solvent, in this case ethanol, in supercritical CO_2 is shown in Figure 3. The high pressure chamber is filled with supercritical CO_2 at a preset pressure and temperature. Two syringe pumps can deliver ethanol, either pure or saturated with CO_2 in the vessel through a stainless steel capillary. The flow rates of these pumps have to be adjusted so that the size of the droplet hanging on the capillary does not change with time. In this case the amount of ethanol delivered into the droplet and dissolving from the droplet into CO_2 are the same. A backpressure regulator (BPR) avoids a pressure increase in the chamber. To prevent an accumulation of ethanol in the fluid in the vessel, it is continuously purged with pure CO_2 from a third syringe pump at low flow rates. By this means, the mass transfer between the solvent droplet and the surrounding supercritical CO_2 is realized under steady state conditions.

To study the occurring mass transport phenomena, the composition of the fluid surrounding the solvent droplet is measured along a line of approx. 2.6 mm with the setup shown in Figure **4**. A frequency-doubled Nd:YAG laser is focused into the measurement chamber (MC) by several lenses (L) and absorbed after leaving the chamber by a beam dump (BD). The scattered light is detected under an angle of 90° by an achromatic lens (AC). A filter (F) blocks elastically scattered light and focuses the remaining inelastically scattered Raman signal on the entrance slit of an imaging spectrometer (600 mm^{-1} grating, 50 µm slit width), whereby the one-dimensional measurement volume (MV) inside the chamber is defined. The imaging spectrometer conserves the spatial information along the measurement volume but disperses the Raman signal from each measurement point into its wavelength components. In this way, the charged coupled device (CCD) camera attached to the imaging spectrometer records an image, where the spatial axis represents the position in the measurement volume, while the spectral axis holds the wavelength information. Each line of the camera image can be drawn as a Raman spectrum similar to those in Figure 2, from which the composition of

the fluid at the corresponding measurement point can be derived. With the chamber mounted on a stage which is movable in all transversal directions, measurements can be carried out at different heights of the droplet.
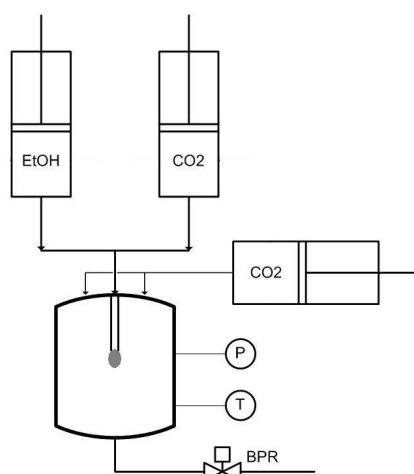

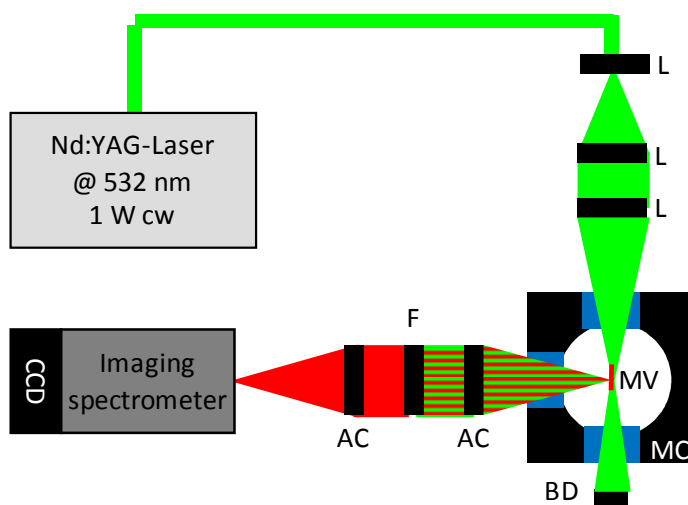**Figure 3:** sketch of the high pressure droplet chamber

Figure 4: Optical setup for the Raman measurements

RESULTS

To carry out compositions measurement by means of Raman spectroscopy, calibration measurements at fixed and preset compositions have to be carried out. To check the possible influence of pressure, temperature, or aggregation state, intense calibration measurements on pure CO_2, pure ethanol, and their mixtures were carried out. The measurements in the pure components over a wide pressure and temperature range revealed that the Raman intensity is only a linear function of density, which is a necessary requirement to evaluate the spectra in a quantitative way. Furthermore, measurements of fixed CO_2 molar fractions were carried out for liquid mixtures of $x_{CO2} = 0.5$ at pressures from 5 MPa up to 9 MPa at 298 K and for gaseous mixtures of $x_{CO2} = 0.98$ at pressures from 3 MPa up to 8 MPa at 343 K. The ratio I_{EtOH}/I_{CO2} of the summarized intensities from 2654 cm^{-1} up to 3099 cm^{-1} (denoted as EtOH band in Figure 2) and from 1179 cm^{-1} up to 1574 cm^{-1} (CO_2 band) are constant for each composition, which qualifies this ratio to quantify mixture compositions from the Raman spectra. Further measurements were made across the complete composition range at constant pressure and temperature. Finally a calibration curve giving the ratio I_{EtOH}/I_{CO2} as a function of the CO_2 mole fraction could be fitted to the data obtained with high coefficient of determination.

Figure 5 shows a hanging droplet of liquid ethanol in the measurement chamber described above filled with supercritical CO_2. The chamber was adjusted to 7.7 MPa and 313 K, which is above the critical point of pure CO_2, but below the MCP for this temperature. Thus, the droplet was realized under so-called subcritical conditions and was stable for a few seconds. The stainless steel capillary had and outer diameter of 3.2 mm and an inner diameter of 1.6 mm. From the image captured with a customary camera, a droplet diameter of approximately 1.1 mm at its lower half can be estimated.

Figure 5: Hanging ethanol droplet in sc CO_2

CONCLUSION

Intense calibration measurements revealed that Raman spectroscopy qualifies for quantitative measurements of composition in high pressure systems. The experimental plant and the measuring chamber enable to receive hanging droplets of liquid solvents in supercritical CO_2 at subcritical conditions of the SAS process. By means of the optical setup described above, the mass transfer across the occurring phase boundaries can be analyzed by measuring compositions along a line in vicinity droplet with a high spatial resolution. Possible common solvents used in the SAS process, which also qualify for Raman measurements as ethanol, 1-propanol, dimethysulfoxide (DMSO), acetone, and hexane, will be studied also in future investigations. For the solvents with an OH-bond, also temperature can be measured in the liquid phase and therefore heat transfer can be taken into account as well. By varying the dimensions and the material of the capillary, even larger droplets may be achieved.

The mass transfer across the phase boundary between the liquid solvent droplet and the supercritical CO_2 occurs in two ways: Firstly, the solvent can evaporate from the droplet and secondly, CO_2 can dissolve into the droplet [11]. To distinguish between these two phenomena, three different modifications of the experiment can be carried out (see Figure 6):

a) If pure liquid solvent is injected in the chamber through the capillary, both mass transport processes are present. In this case, the one-dimensional Raman measurements can be carried out in the supercritical phase surrounding the droplet at different heights, indicated by the dotted lines.
b) If a saturated liquid mixture of solvent and CO_2 is injected, the mass transfer from the bulk into the droplet is suppressed and only the evaporation process can be analyzed, again in the supercritical phase.
c) Furthermore, the chamber can be turned, so that the capillary is at the bottom. If then pure supercritical CO_2 is delivered in the chamber, which is now filled with liquid

solvent, a bubble of supercritical CO_2 will occur. Again, both mass ways of mass transfer can be investigated, but in this case, the measurement volume is located in the liquid phase.
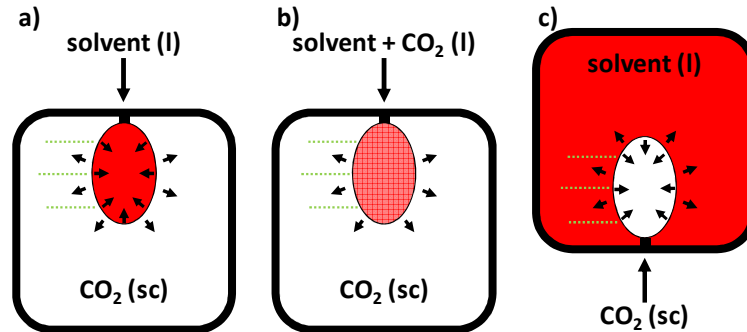

Figure 6: modifications of the experiment

By this means, the two mass transport phenomena can be decoupled. The results of these studies will contribute to understanding and modeling the processes taking place in the SAS process at so-called subcritical conditions, where the pressure is between the critical pressure of CO2 and the MCP of the system CO_2-solvent at the operating temperature.

ACKNOWLEDGEMENTS

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