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Journal Article**Author(s):**

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Publication date:

2005

Permanent link:

<https://doi.org/10.3929/ethz-b-000429296>

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Originally published in:

Review of Scientific Instruments 76(5), <https://doi.org/10.1063/1.1899308>

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Cite as: Rev. Sci. Instrum. **76**, 053904 (2005); <https://doi.org/10.1063/1.1899308>

Submitted: 05 January 2005 . Accepted: 06 March 2005 . Published Online: 22 April 2005

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Characterization of the rapid expansion of supercritical solutions by Fourier transform infrared spectroscopy *in situ*

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(Received 5 January 2005; accepted 6 March 2005; published online 22 April 2005)

A new apparatus for the *in situ* characterization of the rapid expansion of supercritical solutions (RESS) by Fourier transform infrared spectroscopy is presented. The infrared characterization is complemented by particle sizing with a scanning mobility particle sizer, by three-wavelengths-extinction measurements, and by scanning electron microscopy. Several examples show that a wide range of information about particle properties can be obtained with this setup. One new aspect is the possibility to expand into the vacuum which also allows us to investigate the conditions in the collision-free region before the Mach disk. These investigations elucidate that in the free jet region the solvent CO₂ condenses to particles with mean radii >50 nm for pre-expansion pressures between 100–400 bar and temperatures between 298–398 K. © 2005 American Institute of Physics. [DOI: 10.1063/1.1899308]

I. INTRODUCTION

Rapid expansion of supercritical solutions (RESS) of molecular compounds leads to the formation of particles with sizes in the submicrometer range.^{1–4} The RESS process consists in solvating the molecular compound of interest in a supercritical fluid and in rapidly depressurizing this solution through a small nozzle. The rapid expansion leads to high supersaturation and consequently to particle formation. An interesting application of RESS is the micronization of pharmaceutical substances to improve their bioavailability.^{2–6} In this context, supercritical CO₂ is a particularly suitable solvent. Its most important advantages are the low critical data (critical temperature $T_c=304$ K, critical pressure $p_c=7.38$ MPa), the fact that CO₂ is nontoxic, and that it can be easily separated from the particles after their formation.

A problem still not finally resolved is the accurate characterization of the particles *in situ*, for instance, to control the particle formation. Most often, off-line techniques are used to characterize the particles. This includes scanning electron microscopy (SEM) to determine the shape and the size, x-ray diffraction and differential scanning calorimetry for the physical characterization, and high performance liquid chromatography and infrared spectroscopy for the chemical analysis of the particles.^{1,2,7,8} Sometimes, particle sizers [scanning mobility particle sizer (SMPS), aerodynamic particle sizer (APS)] serve for the on-line characterization of the size distribution.^{8–10} These methods lead to comparatively accurate size distributions but are slow (measurement times of about 2 min) and rather difficult to handle. The latter disadvantages do not occur for the size characterization *in situ* with laser light scattering such as the three-wavelengths-extinction measurement (3-WEM) technique.^{11,12} This

method is easy to handle, but it yields only a rough estimate of the size distribution.

Also missing for the better understanding of the RESS is the experimental characterization of the conditions in the collision-free region of the expansion before the Mach disk. One central question concerns the influence of the condensation of the supercritical solvent in this region. Such experimental investigations are a prerequisite for the optimization of the particle formation and are crucial to verify corresponding theoretical predictions.^{2,11,13–17}

In this contribution, we present a new apparatus for the *in situ* characterization of the rapid expansion of supercritical CO₂ solutions. The setup and operation of the apparatus is discussed in Sec. II. One new aspect is the possibility of experimentally investigating also the processes which take place in the region before the Mach disk. For that purpose, we expand the supercritical CO₂ in a pulsed mode into the vacuum, where both the region before and after the Mach disk, can be investigated by *in situ* direct absorption Fourier transform infrared (FTIR) spectroscopy.^{18–20} and 3-WEM.^{11,12} Our first results on the influence of the CO₂ condensation taking place before the Mach disk are reported in Sec. III. Section IV deals with the characterization of organic particles generated with the RESS technique. It is shown that *in situ* FTIR spectroscopy can be used to obtain a wide range of information about different particles properties, i.e. the size distribution, the chemical composition, or structural information.

II. APPARATUS

The new apparatus devoted to the study of organic nanoparticles is divided into two major parts: (1) The generation of the particles by rapid expansion of supercritical solutions (RESS apparatus). A completely new aspect of this part is the possibility to expand directly into the vacuum. This allows us

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FIG. 1. (Color online) Scheme of the experimental setup.

to investigate the conditions in the collision-free region before the Mach disk. (2) The tools to analyze the nanoparticles which include the *in situ* characterization by FTIR spectroscopy and 3-WEM, and the characterization with the SMPS and SEM. The new aspect here is the infrared characterization *in situ*. A scheme of the whole apparatus is depicted in Fig. 1.

A. Particle generation

The apparatus to dissolve organic substances in supercritical CO_2 has been described in a previous article.⁸ The CO_2 gas is first liquefied by a cryostat and then pressurized by a pneumatic pump (Pump 1) to the desired pressure in the extraction unit ($p_{\text{ext}} \leq 400$ bar). The extractor is a heated ($T_{\text{ext}} < 500$ K) high-pressure autoclave which contains a porous filter packed with the substance. After passing the extractor, the supercritical solution enters the heated ($T_R < 500$ K) high-pressure reservoir. During the expansion, the reservoir pressure (i.e., the pre-expansion pressure) $p_R \leq 400$ bar is kept constant by a second pneumatic pump (Pump 2). The nozzle (microliquids GmbH) is positioned in the vacuum chamber and connected to the reservoir with a high-pressure hose. The pinhole nozzle has a variable inner diameter of $d = 20, 50, 100$, or $150 \mu\text{m}$ and a length of $l = 250 \mu\text{m}$ and can be heated ($T_N < 500$ K) independently. The nozzle can be displaced by up to 30 cm relative to the position of spectroscopic investigations with FTIR and 3-WEM. In this way, the expansion can be studied in different regions. A pneumatic valve in front of the nozzle allows to expand the solution in a pulsed mode (pulse duration > 100 ms) into the chamber. The expansion chamber is a

vacuum chamber (volume of about 0.08 m^3) which is connected to a buffer volume of 0.7 m^3 . The buffer volume helps to limit the increase of the pressure p_c in the expansion chamber. The whole vacuum part is evacuated to $p_c = 0.03$ mbar by two rotary piston vacuum pumps (Leybold DK 100 and E 250) connected in parallel. With the $50 \mu\text{m}$ nozzle and a reservoir pressure of $p_R = 400$ bar, the pressure in the chamber typically increases up to 0.16 mbar after a pulse of 0.5 s duration. A pulse duration of 2 s leads to a pressure in the chamber of $p_c = 0.55$ mbar. Such a combination of direct absorption FTIR spectroscopy with intense fluid pulses into the vacuum has been realized for the first time by Suhm and co-workers^{18,19} who have shown that this represents one of the most general and powerful methods to study the vibrational dynamics of small cluster.

B. Particle characterization

The infrared spectra of nanoparticles were recorded *in situ* using a Bruker IFS 66v/S FTIR spectrometer. Infrared spectra are particularly useful to analyze particle properties because they contain information about the size distribution, the chemical composition, and about structural aspects. Despite these advantages, it has—to our knowledge—not been used before for *in situ* investigations of the RESS. In our setup, the supersonic flow is probed radially by the infrared beam, as depicted in Fig. 1. The infrared beam from the Global light source is focused into the center of the expansion by a first off-axis parabolic mirror (327 mm focal length). After passing the expansion, the light is collected by a second off-axis parabolic mirror (327 mm focal length) and a third parabolic mirror (109 mm focal length) focuses the light onto a liquid nitrogen cooled MCT detector. The spectrometer and the detector chamber are separated from the expansion chamber by two KBr windows. The rapid-scan mode of the spectrometer allows us to synchronize the acquisition of infrared spectra with the pulsed expansion. With a scanner velocity of 280 kHz, one scan is recorded in 30 ms at a resolution of 2 cm^{-1} so that several scans can be acquired during one pulse (pulse duration > 100 ms). To get a good signal to noise ratio, we typically accumulate more than 500 scans.

As a complementary method for the *in situ* determination of the size distribution of the particles, we have built a three-wavelengths-extinction-measurement (3-WEM) experiment.^{11,12,21} It is based on extinction measurements $[\ln(I_0/I)]$ of laser light from three different lasers which in our case have the wavelengths 405 nm, 633 nm, and 1064 nm. The three lasers probe the expansion radially, as indicated in Fig. 1. The attenuated laser light is detected by an InGaAs photodiode in case of the infrared laser and by Si photodiodes for the 405 nm and for the 633 nm lasers. The analysis of the experimental data proceeds by a specially designed program which assumes a lognormal size distribution and spherical particles (Mie theory, e.g., Ref. 22). All these assumptions lead to inaccuracies in the size distribution so that the results from 3-WEM have to be regarded as rough estimates of the size distribution (see Sec. IV A and Refs. 9, 12, 21, and 23). The advantages of this method are the high time resolution (μs) and the fact that it can be used under

FIG. 2. (a) 3-WEM: Transmission signals from the three lasers with wavelengths 405 nm, 633 nm, and 1064 nm for a single expansion pulse with a length of $t_{\text{puls}}=2.15$ s. (b) Corresponding infrared spectra for the first 420 ms. All data were recorded in the collision-free region before the Mach disk. Conditions: $p_{\text{ext}}=p_R=400$ bar, $T_{\text{ext}}=T_R=T_N=298$ K.

various experimental conditions (pressure, temperature).

The number size distribution of the aerosol was also measured on line with a scanning mobility particle sizer (SMPS). The SMPS consists of a differential mobility analyzer (TSI 3080L/N) which classifies the particles according to their mobility in an electric field and of a condensation nuclei counter (TSI 3022A) where the particles are optically counted. The SMPS only works at atmospheric pressure and at room temperature and can therefore be used only for certain experiments. Compared with 3-WEM and infrared spectroscopy it leads to more detailed size distributions since it measures the number of particles for each single size and does not rely on an assumption of the type of size distribution. However, the SMPS is much slower than 3-WEM or IR spectroscopy. Typical acquisition times lie around 2 minutes.

To visualize the shape of the nanoparticles and also to determine approximate sizes, we use Scanning Electron Microscopy (SEM). This off-line characterization requires us first to collect the particles which often leads to agglomeration. We collect the samples on a silicon holder covered by a thin gold layer (11 nm). Afterwards the sample is covered

TABLE I. Time A (Fig. 2) until stable expansion conditions are established as a function of the nozzle diameter.

Nozzle diameter/ μm	Time A/ms
50	350
100	120
150	50

again with a second gold layer (7 nm) to avoid evaporation of substances inside the SEM apparatus.

C. Pulsed expansion

For pulsed expansions, it is important to know when stable expansion conditions are reached since only then the particle formation is stable as well. Figure 2 shows data recorded for the expansion of pure CO_2 through the $50\ \mu\text{m}$ nozzle into the vacuum ($p_c=0.03$ mbar). Panel (a) contains the results from 3-WEM for the three different lasers as a function of time, while panel (b) shows the corresponding time-dependent infrared spectra. All data were measured in the collision-free region of the jet about 0.5 cm downstream from the nozzle orifice. The reservoir pressure amounted to $p_R=400$ bar ($=p_{\text{ext}}$) and the nozzle temperature was $T_N=298$ K ($=T_{\text{ext}}=T_R$). Note that under these expansion conditions the CO_2 is in the liquid state, but that the same effects have been observed also in the supercritical region. The opening time of the nozzle was set to $t_{\text{puls}}=2.15$ s. $t=0$ s corresponds to the time when the pneumatic valve was opened. Panel (a) illustrates that the expansion can be separated into three parts: Part A corresponds to the time until stable conditions are reached. This includes the time to open the valve, the time to fill the dead volume between valve and nozzle, and the time to establish a stable expansion. Stable expansion conditions hold during the time interval B. Part C represents the time after the valve is closed, which includes the time to close the valve and the time to empty the volume between the valve and the nozzle. Table I lists the time interval A as a function of the nozzle diameter. It increases with decreasing nozzle diameter which indicates that neither the opening time of the valve nor the filling of the dead volume are the limiting factors, at least not for the two smaller nozzles. The limiting factor is the time to establish a stable expansion in the vacuum chamber.

The signal from 3-WEM does not only arise from scattering by the CO_2 particles, but it also probes density fluctuations in the expansion which are probably dominant in parts A and C of the expansion. By contrast, infrared spectra are only sensitive to absorption and scattering of the CO_2 particles so that they can be used to investigate the formation of CO_2 particles during the stabilization of the expansion. An example is shown in Fig. 2(b) for the $50\ \mu\text{m}$ nozzle and for the first 420 ms of the expansion. During the first 300–350 ms, the shoulder at $2340\ \text{cm}^{-1}$ increases compared with the main peak at $2360\ \text{cm}^{-1}$. After this period, the ratio of the two bands remain stable. We have shown in a previous contribution²⁴ (see also Sec. III A) that the increase of this shoulder reflects an increase in the particle size. That means,

TABLE II. Geometric standard deviation σ , mean particle radius r_0 , and particle number concentration N [see Eq. (1)]. The data from infrared spectra have been obtained from a fit to the experimental data using Mie theory and two different sets of refractive index data (Refs. 31 and 32). The values for σ have been fixed. 3-WEM corresponds to the values obtained from extinction measurements with three different lasers (Ref. 21). Note that for $T_N=298$ K, the solvent CO_2 is in the liquid state.

Method	p_R /bar	T_N /K	σ	r_0 /nm	$N^b/10^8 \cdot \text{cm}^{-3}$
FTIR ^a	400	298	2.1	70	3.9
	400	298	1.8	120	1.6
	400	298	1.6	190	0.8
	400	298	1.4	300	0.2
	400	298	1.2	410	0.2
3-WEM	400	298	~ 2.1	~ 75	~ 1.8
FTIR	100	298	1.4	180	0.1
	400	360	1.4	210	0.2

^aFor each value of σ , r_0 and N correspond to mean values obtained for different experimental spectra and for two different sets of refractive index data (Refs. 31 and 32).

^bValues for N for a path length of $l=1$ cm.

the particle size increases during the stabilization of the expansion (350 ms for the 50 μm nozzle, see Table II) and remains stable afterwards.

III. INFLUENCE OF THE CO_2 CONDENSATION

Typically, the mole fraction of solids or liquids of low volatility in supercritical CO_2 lies below 0.1–0.01.²⁵ Or in other words, the supercritical solution that is expanded in the RESS process mainly consists of CO_2 . Therefore, it is evident that the influence of CO_2 is not negligible upon the particle formation. Within the nozzle itself and some nozzle diameters in front of the nozzle orifice, one expects that, due to the high supersaturation, not only the low-volatile solute but also the CO_2 itself condenses into small particles.^{2,11,13–17} In the present section we show that these solvent particles can really be observed experimentally in the collision-free region before the Mach disk. The sudden temperature and pressure increase taking place at the Mach disk leads again to the evaporation of these solvent particles. As discussed below, these processes can be monitored with *in situ* FTIR spectroscopy.

A. Expansion of pure CO_2

To investigate the condensation/evaporation behavior of the solvent, we have in a first step expanded pure CO_2 at temperatures between $T_{\text{ext}}=T_R=T_N=298$ –398 K and pressures between $p_{\text{ext}}=p_R=100$ –400 bar into our vacuum chamber ($p_c=0.03$ mbar). Figure 3(b) shows the corresponding infrared spectrum which was recorded during the expansion at a distance of about 1 cm in front of the nozzle orifice. Under the experimental conditions used (nozzle diameter $d=50$ μm , $p_R=400$ bar, $T_N=298$ K), this observation point lies in the collision-free jet region. The absorbance scale was expanded to show weak absorption bands and effects due to elastic scattering (slanted baseline; see below), so that the two strong absorption bands ν_2 at ~ 670 cm^{-1} (bending vibration) and ν_3 at ~ 2360 cm^{-1} (stretching vibration) are cut in this figure. The inset in Fig. 3(b) depicts the ν_2 band in

FIG. 3. Survey spectra of CO_2 particles in the region between 600 and 4500 cm^{-1} . (a) Experimental infrared spectrum for particles generated in a collisional cooling cell (Refs. 26 and 27). (b) Experimental infrared spectrum for particles generated with the RESS apparatus (nozzle diameter $d=50$ μm , $p_{\text{ext}}=p_R=400$ bar, $T_{\text{ext}}=T_R=T_N=298$ K). The spectra were recorded at a resolution of 2 cm^{-1} . (c) Simulated infrared spectrum from a fit to the experimental spectrum in trace (b). For the fit we have used the refractive index data from Ref. 31, a Mie model (Ref. 22), and a lognormal distribution [Eq. (1)]. The refined parameters for this fit are $\sigma=2.1$ (fixed), $r_0=65$ nm, and $N=4.5 \times 10^8 \text{ cm}^{-3}$. $\tilde{\nu}$ is the transition wave number.

more detail and Fig. 4(a) shows in expanded view the ν_3 band. The second inset in Fig. 3(b) shows the region of the combination bands $2\nu_2+\nu_3$ and $\nu_1+\nu_3$ in more detail. All these pictures prove that in the free jet region CO_2 is condensed into small particles. To support this statement, Fig. 3(a) shows a corresponding spectrum of small CO_2 particles generated in a collisional cooling cell.^{26,27} Since both spectra show similar band positions and band shapes which are characteristic for CO_2 particles,^{26–28} it is clear that the RESS spectrum in trace (b) represents a particle spectrum. The additional absorptions in Fig. 3(b) that are missing in trace (a) (for instance, the weak broad features in the region between 3500 cm^{-1} and 3800 cm^{-1}) arise from the residual gas phase in the jet (see also the discussion to Fig. 4). Information about the phase of the CO_2 particles can be obtained from the bending vibration ν_2 which is depicted in the inset in Fig. 3(b). The observed splitting of this band indicates that the CO_2 particles are at least partially crystalline and not completely amorphous.²⁹

From the experimental infrared spectra, we have estimated the size of the CO_2 particles. This is an important quantity to know since the condensation/evaporation behavior of the solvent strongly influences the particle formation processes. It is also of interest to verify corresponding theoretical predictions of these processes.^{2,11,13–17} Here, we have used Mie theory²² for spherical particles to estimate the particle sizes by fitting calculated extinction spectra to the experimental infrared spectra. For the particle radii r we assume a lognormal distribution:³⁰

$$df = \frac{1}{\sqrt{2\pi} \ln \sigma} \exp\left(-\frac{(\ln(r/u) - \ln(r_0/u))^2}{2(\ln \sigma)^2}\right) d(\ln(r/u)), \quad (1)$$

with the mean particle radius r_0 and the geometric standard deviation σ as parameters. u is the unit radius. The product

FIG. 4. Infrared spectra of CO_2 particles in the region of the antisymmetric stretching vibration ν_3 . (a) Experimental spectrum for particles generated with the RESS apparatus (nozzle diameter $d=50\ \mu\text{m}$, $p_{\text{ext}}=p_R=400\ \text{bar}$, $T_{\text{ext}}=T_R=T_N=298\ \text{K}$). The spectrum was recorded at a resolution of $2\ \text{cm}^{-1}$. (b) As (a) but recorded at a resolution of $0.25\ \text{cm}^{-1}$. (c) Simulated infrared spectrum from a fit to the experimental spectrum in trace (b). For the fit we have used the refractive index data from Ref. 32, a Mie model (Ref. 22), and a lognormal distribution [Eq. (1)]. The refined parameters for this fit are $\sigma=1.4$ (fixed), $r_0=340\ \text{nm}$, and $N=0.1 \times 10^8\ \text{cm}^{-3}$. $\tilde{\nu}$ is the transition wave number.

$N \cdot l$ of the particle number concentration N and the pathlength l is determined by the absolute values of the extinction measured. The pathlength amounts to about $l=1\ \text{cm}$ at the point of measurement. As input data for the optical constants, we used two different datasets for the real (n) and imaginary (k) part of the refractive index.^{31,32} The first one was derived from bulk data of CO_2 and the second one was obtained from a microscopic model. The parameters σ and r_0 turned out to be highly correlated. Therefore, we have varied σ in a physically reasonable range between about 1.2 to 2.1. The fit results for r_0 and N for different fixed values of σ are listed in Table II. Note that these values correspond to mean values for different fits obtained with the two sets of refractive index data and for different experimental spectra. These data illustrate the correlation between σ and r_0 : Low values of σ correspond to high values of r_0 , and *vice versa*. A simulated spectrum from a fit with the refractive index data from Ref. 31 is depicted in Fig. 3(c). It shows the same slanted baseline, which results from elastic scattering,²² as the experimental spectrum in trace (b). The reproduction of the slanted baseline, however, is only one criterion for a good fit. The second point is the shape of the absorption bands. Figure 4 illustrates this aspect for the ν_3 band with two experimental

spectra in traces (a) and (b). The simulated spectrum in trace (c) is shown as obtained from a fit with the refractive index data from Ref. 32. The two experimental spectra only differ in the following resolution: $2\ \text{cm}^{-1}$ for trace (a) and $0.25\ \text{cm}^{-1}$ for trace (b). The spectrum in trace (b) shows that there is still a residual gas phase in the jet. Due to the lower resolution in trace (a), no single rotational transitions can be distinguished here. The gas phase contribution is merged here with the particle spectrum and therefore it somewhat modifies the band shape of the latter. For instance, it slightly increases the absorbance of the shoulder at $2340\ \text{cm}^{-1}$ marked with an asterisk. The widths of the absorption band in the particle spectrum and the appearance of the shoulder at $2340\ \text{cm}^{-1}$ are characteristic for the size of the particles.²⁴ Both attributes are well reproduced by the corresponding simulation depicted in trace (c). As already mentioned, r_0 and σ are correlated. Therefore, we cannot definitely distinguish from the overall fit results between broader distributions with smaller mean sizes and narrower distributions with larger mean sizes (see Table II). However, the fit results for the region of the ν_3 band alone at least slightly favor narrower distributions ($\sigma \sim 1.4$) with larger mean sizes ($r_0 \sim 300\ \text{nm}$). From this observation and the results summarized in Table II, we finally conclude here that the mean particle radius of the solvent particles lies clearly above $r_0=50\ \text{nm}$. In addition to the infrared results, Table II lists the parameters of the size distribution estimated from 3-WEM.²¹ These values have to be viewed with care because the scattering experiments are also sensitive to density fluctuations and not only to scattering and absorption by the particles (see Sec. II C and Ref. 21). Therefore, we can only say here that the scattering measurements at least do not contradict the infrared results.

The next aspect we have investigated was the pressure and temperature dependence of the particle size. For that, the pre-expansion pressures has been varied between $p_R=100\ \text{bar}$ and $400\ \text{bar}$ at room temperature and the infrared spectra have been measured again immediately in front of the nozzle exit. As expected, we have found a systematic decrease of the mean particle radius r_0 with decreasing pre-expansion pressure. Typically, r_0 decreases by 40% between $400\ \text{bar}$ and $100\ \text{bar}$. As an example, Table II lists the parameters for $p_R=100\ \text{bar}$ and $\sigma=1.4$. We have also found a systematic decrease of the particle size with increasing temperature. Between $298\ \text{K}$ and $360\ \text{K}$ this decrease amounts to 30% (see the example for $\sigma=1.4$ in Table II).

All measurements reported so far have been performed in the collision-free region before the Mach disk immediately in front of the nozzle exit. Since our nozzle is movable (section II), we can also record infrared spectra at different distances from the nozzle exit up to a maximum distance of $30\ \text{cm}$. The integrated infrared extinction decreases about linearly with increasing distance from the nozzle. The reason for this is the quadratic decrease of the particle density and the linear increase of the pathlength for a cone-shaped expansion of the beam. From the infrared spectra measured at different positions we conclude that the particle size is stable before the Mach disk. In the region of the Mach disk, the gas phase residues in the spectra show that the temperature in-

FIG. 5. Infrared spectra of nonadecane particles in the region of the CH-stretching vibrations. (a) Spectrum recorded during the expansion in the collision-free region before the Mach disk 1 cm in front of the nozzle. In this region both CO_2 and nonadecane condense to small particles. (b) Spectrum of pure nonadecane particles. The spectrum was recorded after the end of the pulse and after all CO_2 particles were evaporated. $\tilde{\nu}$ is the transition wave number.

creases. One important result from these measurements is the fact that we still detect particles in the region and several cm after the Mach disk. These particles are only slightly smaller than those probed before the Mach disk. Obviously, the evaporation of the particles takes some time. To estimate this evaporation time, we have measured infrared spectra as a function of time after the pulse has been finished. These spectra clearly show that the size and thus the total amount of condensed CO_2 decrease with increasing time whereas the amount of gas phase CO_2 increases. After about 2 seconds, no particles can be detected anymore. This means that it takes seconds until all solvent particles are evaporated.

B. Expansion of a solution

Figure 5 shows the region of the CH-stretching vibrations of *n*-nonadecane ($\text{C}_{19}\text{H}_{40}$) particles which were generated with RESS. The experimental conditions were equivalent to those used in Figs. 3(b) and 4(a) ($p_c = 0.03$ mbar, $p_{\text{ext}} = p_R = 400$ bar, $T_{\text{ext}} = T_R = T_N = 298$ K). For these conditions, the mole fraction of nonadecane lies above 0.02.²⁵ The infrared spectrum in Fig. 5(a) was recorded at a distance of 1 cm from the nozzle exit in the collision-free region before the Mach disk. The spectrum in trace (b) was measured several minutes after the end of the expansion pulse when all CO_2 is already evaporated. Thus, trace (b) depicts a spectrum of pure nonadecane particles, i.e., of the final product (see Sec. IV).

In the collision-free region of the expansion, CO_2 and nonadecane both exist as small particles due to the supersaturation and subsequent condensation upon expansion. But, it is not clear whether the two components form (statistically) mixed particles or whether nonadecane first condenses to small particles which then act as condensation nuclei for the more volatile CO_2 (coated particles). From the CO_2 infrared absorption bands, we cannot distinguish between these two cases. The amount of CO_2 in the solution is much higher than the amount of nonadecane. Therefore, one expects no measurable changes of the CO_2 infrared extinction bands of the mixture compared with those for the pure CO_2 particles [Figs. 3(b) and 4(a)]. This is exactly what we also find experimentally. The CO_2 particle bands of the mixture and of the pure particles are identical. In contrast to the CO_2 bands, the nonadecane bands could in principle be influenced by the two types of particles mentioned (mixed or coated particles). For CO_2 -coated nonadecane particles, we would expect the same spectrum as for pure nonadecane particles since the influence of the CO_2 coating is negligible. But for (statistically) mixed particles, the matrix effect could shift the bands compared with pure nonadecane. Unfortunately, the matrix effects for nonadecane in CO_2 is not known so that the absence of a shift does not finally exclude mixtures. The comparison of Figs. 5(a) and 5(b) shows that experimentally no shift is observed between the CO_2 /nonadecane particles and the pure nonadecane particles. Therefore from the infrared spectra we can only conclude that the formation of CO_2 -coated nonadecane particles is in agreement with the experimental results but that mixed particles cannot be finally excluded. However, the preference of coated particles is further supported by the fact that nonadecane is much less volatile than CO_2 and thus condenses first probably already within the nozzle.^{2,11,13–17}

The conditions and processes before the Mach disk certainly influence the properties of the final particles. But we believe that much more important factors for the final product are the processes taking place at and after the Mach disk and the manner in which the final product is collected. All these factors can lead to coagulation and agglomeration of primary particles as shortly discussed in the following section.

IV. CHARACTERIZATION OF THE FINAL PRODUCT

For the characterization of the final products, we can use four different methods, as described in Sec. II: FTIR spectroscopy *in situ* is used to determine the size distribution, the chemical composition, and the phase behavior. 3-WEM *in situ* and on-line measurements with the SMPS serve to determine the size distribution. And SEM is used to analyze the shape and the size of the particles. This is shortly described in the following two subsections for the example of two different organic aerosols.

A. Phenanthrene particles

In a previous study,⁸ we have investigated the properties of phenanthrene ($\text{C}_{14}\text{H}_{10}$) particles. These particles were generated by expanding a CO_2 /phenanthrene solution

FIG. 6. (a) SEM image of phytosterol particles. (b) Part of the infrared spectrum of pure phytosterol particles (85% β -sitosterol, 10% stigmasterol, and 5% campesterol). The infrared extinction is stable for more than 15 min after the end of the pulse. $\tilde{\nu}$ is the transition wave number. Under the conditions used ($p_{\text{ext}}=p_R=400$ bar, $T_{\text{ext}}=T_R=T_N=298$ K), the mole fraction of phytosterol in CO_2 lies around 0.0001 (Ref. 4).

against a cell pressure of $p_c=1$ bar. Under the conditions used ($p_{\text{ext}}=p_R=100\text{--}400$ bar, $T_{\text{ext}}=T_R=T_N=298\text{--}398$ K), the mole fraction of phytosterol in CO_2 lies between 0.0001 and 0.005.²⁵ The size distribution and the shape were characterized off-line by SEM and on-line with the SMPS. The particles were found to be nearly spherical with mean radii around $r_0=120$ nm and geometric standard deviations of about $\sigma=2.2$. The focus of this previous contribution was the determination of refractive index data in the mid-infrared region. These optical data were derived from infrared spectra measured on line in a long-path absorption cell. As mentioned there, the main disadvantage of the on-line characterization was that the size distribution and the infrared spectrum could not be recorded exactly at the same position and time which can in principle lead to inaccuracies of the optical data. With the new apparatus we have overcome these deficiencies and can now use the new setup to verify the previous data. For that purpose, we have repeated the measurements several times and determined a new set of refractive index data for each measurement. This allows us to estimate the uncertainty of the optical data which was determined to lie around 20%. We have found that the pre-

viously determined data lie well within this range. The corresponding refractive index data together with a description of the estimated uncertainties are given in Ref. 33.

Our previous study⁸ showed that similar size distributions were obtained from SEM and from the SMPS measurements. With the new apparatus, we can compare the two methods with the results from 3-WEM. The analysis with 3-WEM is based on the assumption of spherical particle shapes. Since the phytosterol particles are nearly spherical the 3-WEM should also lead to similar results as SEM and SMPS. But in contrast to this expectation, the 3-WEM systematically gives larger mean radii and smaller geometric standard deviations compared with the two other methods. The radii are overestimated by up to 40% and the standard deviations are underestimated up to 20%. A similar behavior was already observed in previous studies which compared 3-WEM with other sizing methods.^{9,12,21,23} At the moment we cannot explain this behavior, but since it is obviously systematic it should always be taken into account when interpreting the data from 3-WEM.

Although 3-WEM only gives a very rough estimate of the size distribution, it is especially useful when high time resolution (μs) is required or the pressure and temperature differ from atmospheric conditions. The SMPS and SEM are of only limited use under such conditions. The time resolution allows us to investigate time-dependent processes in an aerosol. For example, we can measure the settling velocity of a phytosterol aerosol as a function of the pressure p_c in the expansion chamber. With the 3-WEM, we have also investigated the influence of the cell pressure p_c on the sizes of the aerosol generated. For that purpose, two different aerosols were generated by expanding the CO_2 solution against a cell pressure of $p_c=0.03$ mbar and $p_c=960$ mbar, respectively. We have found that the particles generated under vacuum conditions have smaller mean radii by about 30% and larger geometric standard deviations by about 30% than the particles generated at 960 mbar. Whether or not this observation is a general trend will be the subject of further investigations.

B. Phytosterol particles

As a second example, we have investigated the agglomeration behavior of phytosterol (85% β -sitosterol, 10% stigmasterol, and 5% campesterol) particles generated with RESS. β -sitosterol can be used as an additive for cosmetic substances or as an agent to reduce the amount of cholesterol in the human blood. It has been demonstrated in previous contributions^{4,34} that the expansion of a binary mixture of phytosterol/ CO_2 leads to strongly agglomerated particles with a spongy structure. Figure 6(a) shows a part of this spongy structure which consists of agglomerated primary particles with radii around 50 nm. Part of the FTIR spectrum of phytosterol is depicted in Fig. 6(b). Türk and co-workers have recently demonstrated that the agglomeration can be suppressed by expanding a ternary mixture of phytosterol/eudragit/ CO_2 (Refs. 5 and 7). It is possibly the coating of the particles with eudragit that prevents the agglomeration.

Our aim in the present investigation was to find out more about the question where the agglomeration of the phy-

tosterol particles takes place. In principle, the particles can agglomerate at the Mach disk, after the Mach disk in the gas phase until the samples for the SEM examination are taken, or during the collection of the particles on the sample holder for the SEM examination. We cannot make firm statements of the processes taking place at the Mach disk from our measurements. The reason for that are the density fluctuations appearing in this region which are also monitored by 3-WEM (or FTIR) and thus falsify the results for the size distributions. We can only measure the static aerosol in the chamber after the pulse has finished. Both FTIR and 3-WEM hint that the phytosterol particles are quite small ($r_0 \sim 50$ nm, $\sigma \sim 1.8$) immediately after the pulse and after all CO₂ has evaporated. Note that this mean radius is similar to the radius of the primary particles visible in Fig. 5(a). Therefore, we do not believe that the predominant processes for the formation of the spongy structures take place at the Mach disk. The same statement seems to be true for subsequent agglomeration processes in the static aerosol with time. Both the infrared signal and the 3-WEM signal are almost completely stable for more than 15 min after the end of the pulse. This means that the majority of the particles in the gas phase are very small and stay small (no agglomeration). Bigger particles or agglomerates would settle down in our chamber and thus lead to a decrease of the extinctions for FTIR and 3-WEM. For comparison, settling of the phenanthrene particles with mean radii around 200 nm leads to a decrease of the extinction by 70% already after 10 min. From that we conclude that the agglomeration predominantly takes place while the samples for the SEM measurements are taken. To support this, we have compared two different sampling mechanisms. In the first case, the particles were collected directly in front of the RESS expansion which resulted in very strong agglomeration. In the second case, we have only collected the particles that settle down from the gas phase during two hours. This sample also shows agglomerates but also many smaller single particles.

ACKNOWLEDGMENTS

We gratefully acknowledge the collaboration with and the support by Professor Dr. Martin A. Suhm. Special thanks go to Werner Noack for his constant help and to Volker Meyer, Andreas Knorr, and their workshop teams. This project was supported by funds from the Deutsche Forschungsgemeinschaft (Grant No. SI 833/1-2, SFB 602, and GRK 782) and from the Fonds der Chemischen Industrie.

- ¹D. W. Matson, J. L. Fulton, R. C. Petersen, and R. D. Smith, *Ind. Eng. Chem. Res.* **26**, 2298 (1987).
- ²J. W. Tom and P. G. Debenedetti, *J. Aerosol Sci.* **22**, 555 (1991).
- ³J. Jung and M. Perrut, *J. Supercrit. Fluids* **20**, 179 (2001).
- ⁴M. Türk, P. Hils, B. Helfgen, K. Schaber, H.-J. Martin, and M. A. Wahl, *J. Supercrit. Fluids* **22**, 75 (2002).
- ⁵M. Türk, P. Hils, K. Hussein, and M. Wahl, *Produktgestaltung in der Partikeltechnologie*, edited by U. Teipel (Fraunhofer-IRB, Stuttgart, 2004), pp. 337–386.
- ⁶M. Türk and M. Wahl, *Proceedings of the International Congress for Particle Technology*, PARTEC 2004, Nürnberg, 16–18 March (2004).
- ⁷M. Türk, *Chem.-Ing.-Tech.* **76**, 835 (2004).
- ⁸D. Hermsdorf, A. Bonnamy, M. A. Suhm, and R. Signorell, *Phys. Chem. Chem. Phys.* **6**, 4652 (2004).
- ⁹J. Meyer, M. Katzer, E. Schmidt, S. Cihlar, and M. Türk, *Proceedings of the World Congress on Particle Technology* 3, 6–9 July 1998, Brighton, UK.
- ¹⁰D. M. Ginosar, W. D. Swank, R. D. McMurtrey, and W. J. Carmack, *Proceedings of the 5th International Symposium on Supercritical Fluids*, Atlanta, GA, 8–12 April 2000.
- ¹¹B. Helfgen, P. Hils, Ch. Holzknecht, M. Türk, and K. Schaber, *J. Aerosol Sci.* **32**, 295 (2001).
- ¹²K. Schaber, A. Schenkel, and R. A. Zahoransky, *Tech. Mess.* **61**, 295 (1994).
- ¹³P. G. Debenedetti, *AIChE J.* **36**, 1289 (1990).
- ¹⁴M. Türk, *J. Supercrit. Fluids* **18**, 169 (2000).
- ¹⁵M. Weber, L. M. Russell, and P. G. Debenedetti, *J. Supercrit. Fluids* **23**, 65 (2002).
- ¹⁶M. Weber and M. C. Thies, *Supercritical Fluid Technology in Material Science and Engineering*, edited by Ya-P. Sun (Marcel Dekker, New York, 2002).
- ¹⁷B. Helfgen, M. Türk, and K. Schaber, *J. Supercrit. Fluids* **26**, 225 (2003).
- ¹⁸Th. Häber, U. Schmitt, C. Emmeluth, and M. A. Suhm, *Faraday Discuss.* **118**, 331 (2001).
- ¹⁹Th. Häber, U. Schmitt and M. A. Suhm, *Phys. Chem. Chem. Phys.* **1**, 5573 (1999).
- ²⁰A. Bonnamy, R. Georges, A. Benidar, J. Boisssoles, A. Canosa, and B. R. Rowe, *J. Chem. Phys.* **118**, 3612 (2003).
- ²¹R. Ueberschaer, Diploma thesis, University of Göttingen, 2004.
- ²²C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles* (Wiley-Interscience, New York, 1998).
- ²³S. Cihlar, Doctoral thesis, VDI GmbH, Düsseldorf, 2000.
- ²⁴R. Signorell, *Mol. Phys.* **101**, 3385 (2003).
- ²⁵K. D. Bartle, A. A. Clifford, S. A. Jafar, and G. F. Shilstone, *J. Phys. Chem. Ref. Data* **20**, 713 (1991).
- ²⁶M. K. Kunzmann, R. Signorell, M. Taraschewski, and S. Bauerecker, *Phys. Chem. Chem. Phys.* **3**, 3742 (2001).
- ²⁷R. Signorell and M. K. Kunzmann, *Chem. Phys. Lett.* **371**, 260 (2003).
- ²⁸M. K. Kunzmann, Doctoral thesis, Cuvillier, Göttingen, 2002.
- ²⁹M. Falk, *J. Chem. Phys.* **86**, 560 (1987).
- ³⁰W. C. Hinds, *Aerosol Technology* (Wiley Interscience New York, 1999).
- ³¹J. A. Roux, B. E. Wood, and A. M. Smith, “IR optical properties of thin H₂O, NH₃, and CO₂ cryofilms,” AEDC-TR-79-57 (AD-A074913), September 1979.
- ³²A. Bonnamy, M. Jetzki, and R. Signorell, *Chem. Phys. Lett.* **382**, 547 (2003).
- ³³<http://wwwuser.gwdg.de/~rsignor/refindex.htm>.
- ³⁴M. Türk, B. Helfgen, P. Hils, R. Lietzow, and K. Schaber, *Part. Part. Syst. Charact.* **19**, 327 (2002).