

# Determination of single-particle drying kinetics in an acoustic levitator

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## Abstract

A novel technique for the determination of single-particle drying kinetics in a closed 45 kHz acoustic levitator is presented. Practical handling is trouble-free, the moisture content of the outlet air stream is measured online by a high accuracy dew point hygrometer. Experimental data show low noise and can easily be transformed to drying curves. Investigations with  $\gamma\text{-Al}_2\text{O}_3$  have been carried out at different air velocities and moderate temperatures. The resulting drying curves are comparable to previous findings from a drying channel or a microbalance. Slightly higher drying rates and a lower critical moisture content in the levitator could indicate moderate interaction between the ultrasonic waves and the drying process. © 2002 Elsevier Science B.V. All rights reserved.

*Keywords:* Acoustic levitator; Single particle; Drying kinetics; Dew point hygrometer

## 1. Introduction

The acoustic levitator is an instrument suitable for the investigation of kinetics at particles or drops. At the authors' laboratory both the drying of single particles and the removal of ammonia from single water drops at normal and low pressure have been investigated in a levitator. Results from degasification experiments have been obtained by optical methods (CCD-camera) as well as by means of thermocouples [1]. Continuous, online analysis of ammonia in the outlet air is not possible, as an exact instrument for this purpose does not exist. The situation is different for drying experiments, which will be in the focus of the present communication. We will show that in this case the concentration of water vapor in the outlet purge air stream can be determined accurately by means of a dew point hygrometer. This novel technique enables the determination of single-particle drying curves in a direct way.

Single-particle drying curves constitute the basis for convective dryer design (e.g. for fluidized beds, see [2]). As the industrial products to be dried are often fine-grained, there is permanent need for accurate and efficient methods of measuring drying curves of even quite small single particles.

Some shortcomings in the investigation of particles with a diameter between 1.0 and 2.0 mm on a microbalance or

in a drying channel (drying tunnel) have been discussed in detail previously [3,4]. Measurements for a single particle on a microbalance are restricted to ambient conditions. The main drawback of investigations in a drying channel is the necessity of measuring for an assemblage of particles, glued on a net, because balances that are sensible enough for investigation of one single particle are not suitable for measurements in a drying channel. The data obtained by both methods scatter considerably, and have to be carefully smoothed.

Another disadvantage of both techniques, the contact of the particles to solids, i.e. the scale, the net, or some other device, can be avoided by investigations in the acoustic levitator. In this equipment, the particle is suspended by acoustic waves [1].

There are two possible ways to measure drying kinetics in a closed levitator: one is to optically record the displacement of the particle from its neighboring pressure node in the course of the drying process. Provided that the correlation between particle mass and position is known, the drying curve can be derived. In the present work a second, completely different, technique is introduced. The levitator is closed, and a certain purge of preconditioned drying air flows through it and around the particle. The moisture content of the outlet air stream is measured. To this purpose, not the usual infrared gas analyzer, but a high accuracy dew point hygrometer has been applied.

In this work, the resulting drying curves and normalized drying curves [5] of single particles (material:  $\gamma\text{-Al}_2\text{O}_3$ ,  $d_p \approx 1.8$  mm) measured in a 45 kHz acoustic levitator at different air velocities are presented and compared to results from other techniques.

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### Nomenclature

$A$	surface area of the particle ( $\text{m}^2$ )
$d$	diameter (m)
$m_{\text{dry}}$	mass of dry particle (kg)
$m_{\text{wet}}$	mass of moisture-saturated particle (kg)
$\dot{m}$	drying rate per particle surface area ( $\text{kg}/(\text{m}^2\text{s})$ )
$\dot{M}$	mass flow rate of dry air ( $\text{kg}/\text{s}$ )
$T$	temperature ( $^{\circ}\text{C}$ )
$t$	time (s)
$u$	air velocity (m/s)
$X$	solids moisture content (dry-based) ( $\text{kg H}_2\text{O}/\text{kg solids}$ )
$Y$	gas moisture content ( $\text{kg H}_2\text{O}/\text{kg gas}$ )

### Greek letters

$\beta$	mass transfer coefficient (m/s)
$\varepsilon$	porosity
$\eta$	dimensionless solids moisture content
$\dot{\nu}$	dimensionless drying rate
$\rho_{\text{g}}$	gas density ( $\text{kg}/\text{m}^3$ )
$\varphi$	relative humidity

### Subscripts, superscripts

I	first drying period
cr	critical point (end of first drying period)
eq	hygroscopic equilibrium
in	at inlet
out	at outlet
p	particle

## 2. Method of measurement

The apparatus used for the investigations is depicted in Fig. 1. The acoustic 45 kHz-levitator is closed, a glass cylinder surrounds a reaction chamber of 10 ml, the cross-sectional area is  $1.9 \text{ cm}^2$ . An important task is to locate the particle inside the levitator close to a pressure node, so that it can be suspended. To this purpose the following procedure has been applied: first, a droplet of water was positioned close to a pressure node with the help of a syringe through a septum at the top of the levitator. Then, the wet particle was placed into the suspended droplet with the help of tweezers through an aperture at the side of the glass cylinder. The effect of this procedure is stabilization of the particle by surface tension of the droplet.

Hence, first the water of the droplet evaporates. Subsequently, and easily identifiable from the measured data, the drying of the particle follows. For calculation of the drying curve, the mass of the moisture-saturated particle is determined immediately before measurement. In this way, the additional amount of water caused by the droplet does not influence the moisture balance. The aperture at the side of the glass cylinder is closed during the drying experiment.

The moisture content of the outlet air has been determined by a dew point hygrometer. This instrument turned out to be both, sensitive enough for the detection of even very small amounts of moisture, and suitable for continuous, online measurements. Fig. 2 shows an example of evaluation of measured dew point data.

Fig. 2a shows, that the original data are quite smooth, so that they can be used directly for the calculation of the drying curve. Here, a first section (about 8 min) with

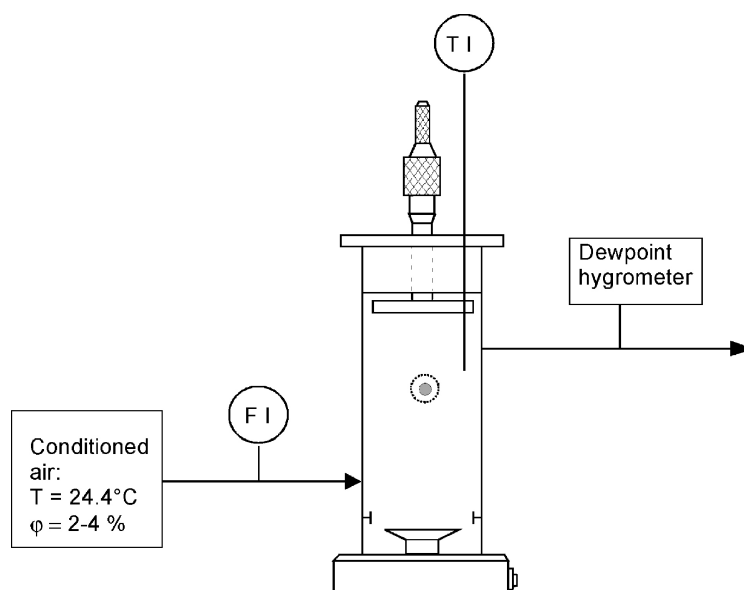


Fig. 1. Experimental setup for drying measurements in a levitator.

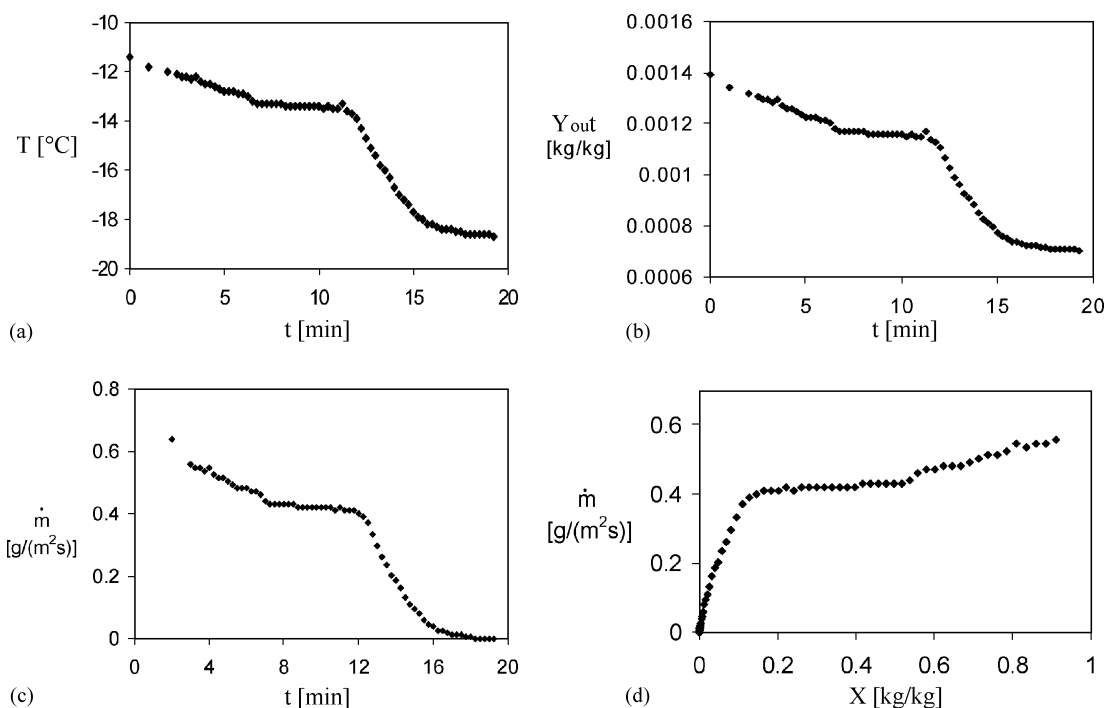


Fig. 2. Example of evaluation: (a) original data, dew point vs. time; (b) moisture content of outlet air vs. time; (c) drying rate vs. time; (d) drying rate vs. solids moisture content.

falling dew point can be distinguished which refers to the evaporation of the droplet used for positioning of the particle and to a thermal transient. Transformation of the measured data to drying curves is straightforward: the dew point data are calculated into partial pressure of water by means of the Antoine equation. From the partial pressure data the moisture content of outlet air (Fig. 2b) and thereupon the drying rate (Fig. 2c) are easily obtained, solution of the moisture balance finally leads to the drying curve (Fig. 2d).

### 3. Results

For the present work, spherical single particles consisting of  $\gamma$ - $\text{Al}_2\text{O}_3$  with a porosity of  $\varepsilon \approx 0.7$  have been investigated in a 45 kHz acoustic levitator at different air velocities. This material is strongly hygroscopic, a desorption isotherm has been determined in [6]. In Table 1 the drying conditions are listed along with the mass of the dry and the moisture-saturated particles.

Before starting the experiments, the particles stayed for 24 h under vacuum in water. The mass of dry particles has been determined after drying for 24 h at 130 °C. The air used in the drying experiments had a temperature of 24.4 °C. According to Table 1, the temperature inside the levitator, close to the particle, was about 28 °C, due to the energy input of the ultrasonic waves. The relative moisture content of the inlet airstream varied between 2 and 4%. Measurements

at significantly higher temperatures turned out to be problematic, because the location of the pressure nodes changes with temperature and therefore, positioning of the particle becomes difficult. Experiments carried out between 25 and 30 °C are well reproducible. The air velocity has been varied between 0.020 and 0.088 m/s. If experiments are carried out with lower air velocities, small leaks within the apparatus can become significant. At air velocities higher than 0.065 m/s the moisture content of the outlet air is too low. As a consequence, the change of the dew point in the course of the drying experiment is too small for accurate derivation of the drying curve. The last column shows the accuracy of the overall mass balance (the relation between the mass difference of the wet and dry particle and the mass of the removed water calculated by integration of the outlet moisture content). By  $t_0$ , (see legend of Table 1), the

Table 1  
Conditions of drying experiments<sup>a</sup>

$u$ (m/s)	$T$ (°C)	$\varphi$	$d_p$ (mm)	$m_{dry}$ (mg)	$m_{wet}$ (mg)	Balance control
0.020	28.2	0.037	1.84	3.586	5.69	0.95
0.042	28.1	0.030	1.81	3.380	5.54	0.98
0.042	28.1	0.029	1.78	3.225	5.15	0.96
0.065	28.2	0.026	1.82	3.455	5.59	0.98
0.088	28.1	0.030	1.84	3.470	5.78	–

<sup>a</sup> In the last column the ratio  $(m_{wet} - m_{dry}) / (\dot{M} \int_{t_0}^t (Y_{out} - Y_{in}) dt)$  is given.

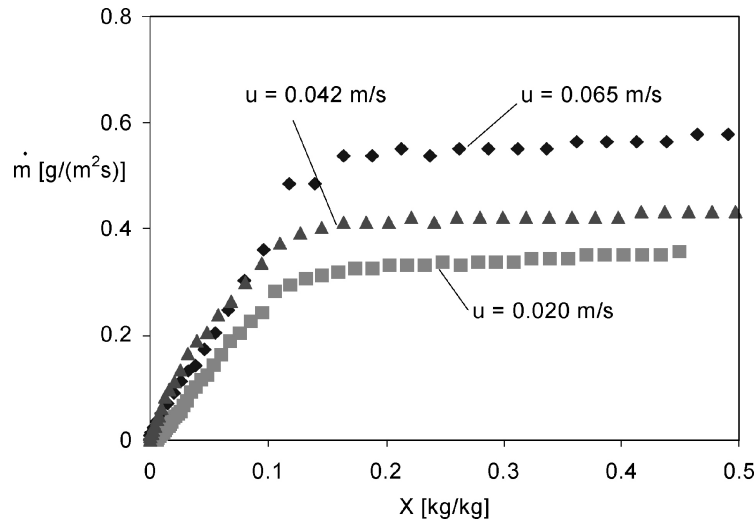


Fig. 3. Measurements at different air velocities.

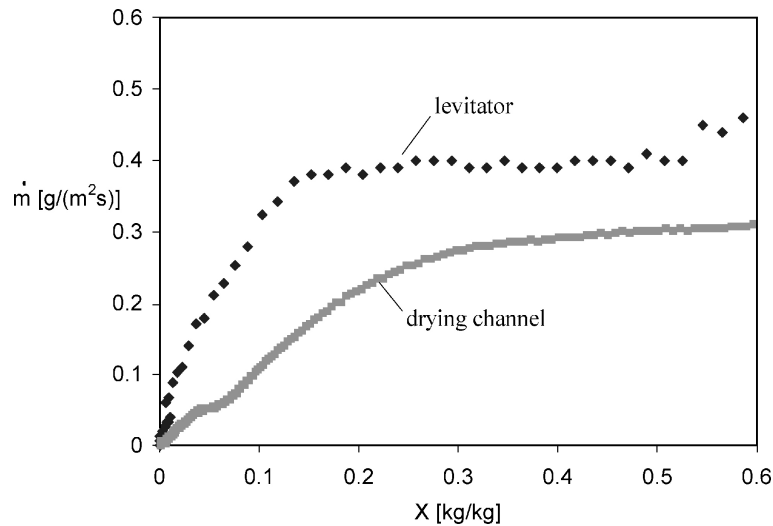


Fig. 4. Comparison of drying curves from two different methods: levitator,  $T = 28^\circ\text{C}$ ;  $u = 0.042\text{ m/s}$ ; drying channel,  $T = 30^\circ\text{C}$ ;  $u = 0.048\text{ m/s}$ .

point of time is indicated, when the drying of the particle starts; (the drying of the waterdrop surrounding it is not considered).

### 3.1. Drying curves

In Fig. 3 drying curves obtained at three different air velocities, ranging between 0.020 and 0.065 m/s are presented. For interpretation of these drying curves comparison with results from other techniques seems reasonable. Therefore, the data gained in the levitator at an air velocity of 0.042 m/s is shown in Fig. 4 together with the drying curve obtained at similar conditions ( $u = 0.048\text{ m/s}$ ,  $T = 30^\circ\text{C}$ ) in the drying channel.

By comparison of the data it can be easily recognized that the drying rates of channel experiments are lower than the

results obtained from measurements in the levitator.<sup>2</sup> This is partly due to the circumstance, that in the case of measurements in the drying channel a certain area of the particle surface is closed by the glue used for fixing the particles on the net. On the other hand, an increase of gas-side mass transport by about 30% is generally observed during acoustic levitation due to the ultrasonic waves [7]. Another difference between the two drying curves of Fig. 4 is a shift in the

<sup>2</sup> Calculation of the first period drying rate from Sherwood numbers after [9] yields  $\dot{m}_1 = 0.41\text{ g/(m}^2\text{s)}$  for the conditions of Fig. 4. Without enhancement of the gas-side mass transfer by acoustic streaming this should be the maximum of attainable drying rate. Notice, however, that actual drying rates are expected to be lower for the investigated, highly hygroscopic material, even without any intraparticle kinetic inhibition. Partial pressure reduction, caused by the equilibrium of sorption, has to be taken into account, as elaborated in [6].

critical moisture content (drying channel:  $X_{cr} \approx 0.3$ , levitator:  $X_{cr} \approx 0.15$ ). It is a common finding, that higher drying rates lead to higher critical moisture [8]. This kind of behavior has been observed in the course of comparisons of measurements with a similar material ( $\gamma\text{-Al}_2\text{O}_3$ ,  $d_p = 1.1$  mm) by microbalance ( $X_{cr} \approx 0.2$ ), drying channel ( $X_{cr} \approx 0.3$ ) and thin layer ( $X_{cr} \approx 0.37$ ) [3]. However, as the two drying experiments of Fig. 4 have been carried out at similar conditions, the same value of  $X_{cr}$  has been expected. The fact that values of  $X_{cr}$  from levitator experiments appear to be lower than respective values from experiments in the drying channel could be an indication for an influence of the acoustic field on intraparticle drying kinetics. This aspect has, still, to be clarified.

### 3.2. Normalized drying curves

To distinguish between gas-side and particle-side kinetics, the drying curves have been normalized after van Meel [5] to the dimensionless variables

$$\dot{v} = \frac{\dot{m}}{\dot{m}_1}, \quad (1)$$

$$\eta = \frac{X - X_{eq}}{X_{cr} - X_{eq}}. \quad (2)$$

As  $\gamma\text{-Al}_2\text{O}_3$  is a strongly hygroscopic material, the first drying period is influenced by the equilibrium of sorption. The respective isotherm has to be considered in the calculation of the reference drying rate

$$\dot{m}_1 = \rho_g \beta A [Y_{eq}(X, T_p) - Y], \quad (3)$$

in a way that has been described in detail in [6]. Applying the method of these authors the results of Fig. 5 have been obtained. There, the normalized drying curves corresponding to the three drying curves with different air velocities of Fig. 3 are presented. An average normalized drying curve (full line), is also plotted.

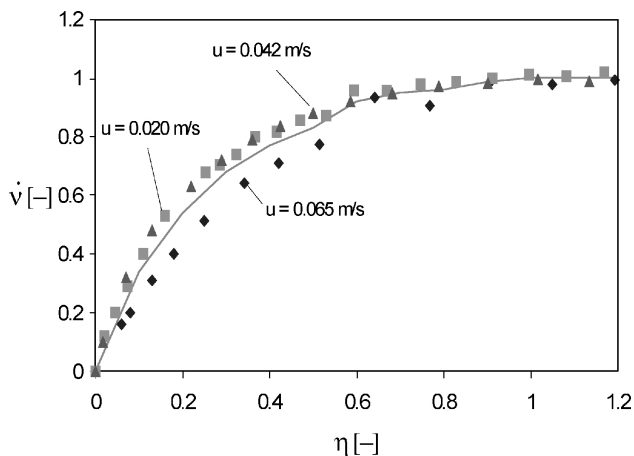


Fig. 5. Normalized drying curves for experiments in the levitator at three different air velocities ( $X_{cr} = 0.15$ ).

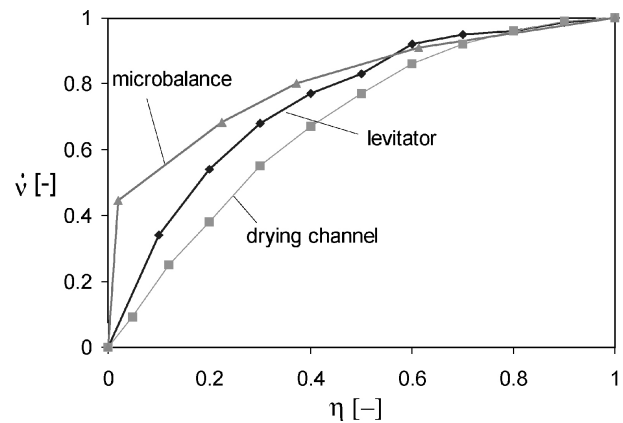


Fig. 6. Normalized drying curves obtained by different methods of measurement (levitator,  $X_{cr} \approx 0.15$ ; drying channel,  $X_{cr} \approx 0.03$ ; microbalance,  $X_{cr} \approx 0.2$ ).

As Fig. 5 reveals, the three individual normalized drying curves correlate well with each other. The resulting average normalized drying curve is compared in Fig. 6 to average normalized drying curves gained from experiments in a drying channel and on a microbalance.

From measurements with a similar material on a microbalance, in a drying channel and in a thin layer it could be observed that higher drying rates lead to more linear kinetics [3]. As the drying rates of the experiments in a drying channel are comparable to those obtained in the levitator, the normalized drying curves are expected to be similar in shape. This is approximately verified from the data of Fig. 6, though the normalized drying rate curves gained by the two last-mentioned methods are not completely identical.

## 4. Conclusion

The purpose of this work has been to test the acoustic levitator as an instrument, for the determination of single-particle drying curves. Measurements of drying kinetics in the levitator turned out to be easy to handle and well reproducible, only little preparation of the experiments is necessary. The measured dewpoint data can be transformed in a straightforward way into drying curves. On the other hand, the range of operating conditions which can be realized in the levitator is quite narrow, especially with respect to temperature. As the comparatively low value of  $X_{cr}$  indicates, the drying behavior may, to a certain extent, be influenced by the ultrasonic field. Nevertheless, the resulting drying curves are considered to be suitable for practical design calculations.

Another technical innovation has been applied within the development of the new method: online measurement of the outlet moisture content of the drying air by means of a dew point hygrometer. This procedure is especially promising, because not necessarily restricted to experiments in a levitator. Some small chamber with a mechanically fixed particle, but without the necessity of weight-determination,

(a non-gravimetric drying microchannel), could be an attractive alternative. As pointed out, hygrometric outlet data are almost free of scatter, complicated methods of smoothing do not have to be employed. Infrared spectrometers as usually applied for the online measurement of moisture contents are not suitable for single particle investigations, because they are not sensitive enough.

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