Basic Preexaminations of Inline Measurements of Droplet Size Distributions by Statistical Extinction Method

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Abstract

The statistical extinction method provides the construction of a sensor which is able to monitor spray processes inline by measuring a mean droplet size. The objective of this study is to examine, if the statistical extinction method can be upgraded to measure a droplet size distribution in addition. Therefore, additional independent measurement values have to be detected by the sensor.

The droplet size detected by a sensor based on the statistical extinction method depends on the cross section area of the laser beam. If the projected droplet cross section is smaller than the laser beam cross section, the laser beam is extincted over the projected cross section area of the droplet. If the droplet is larger than the laser beam, the whole laser beam is extincted, but the extincted cross section area is smaller than the projected droplet cross section area. To measure droplet size distributions a sensor with nine laser beams with different diameters is constructed. All the laser beams are extincted by the illuminated part of the spray which gives additional independent measurement values.

To prove suitability of this upgrade, some theoretical experiments with the upgrade are presented. Finally one process spray is analyzed with the new sensor.

Introduction

There is a need for inline sensors for the monitoring of process sprays, which are able to measure the size of droplets or particles, their concentration, and spatial distribution. The knowledge of the droplet size is of particular importance in many spray processes because it influences mass transport and thermodynamic characteristics of the droplet phase by the generated mass transfer surface. Spray drying processes are highly depending on vaporization and evaporation effects which can be affected, among other features, by droplet size and their concentration.

Measurement techniques which are able to measure these values may improve the understanding of spray drying and provide a better inline control of drying processes. An inline process control allows improving the quality of drying products and facilitates a reduction of degraded material and costs. The inline measurement of a mean droplet size fulfills the requirements of an inline process control because changes of the process parameters can be detected. To improve the understanding of spray processes and to simplify the process design, especially the knowledge of the relationship between the spray parameters (droplet size distribution, droplet concentration, and propagation speed) and the generated particles (size distribution, structure) is fairly interesting.

Existing inline measurement devices for the examination of sprays are usually based on light scattering, phase Doppler or imaging methods. With light scattering methods droplet size distributions can be measured. Phase Doppler methods provide the measurement of droplet size distributions and droplet velocities. A combination of different imaging techniques facilitates the measurement of droplet size distributions, droplet velocities, droplet shapes, and droplet concentrations. All these measurement techniques require optical components, e.g. lenses or photodiodes. These components must be arranged in different geometric axes and partially even in different planes. In order to position these components in drying towers several notches in the outer wall of the tower are necessary. Additionally, components positioned in the tower have to be protected against fouling and thermal impact. Because of these difficulties the measurement techniques named above are not used for inline monitoring of drying processes yet.

The statistical extinction sensor (Fig. 6, subsequently referred as to SE-Sensor) provides the inline measurement of a mean droplet size and the concentration of the droplets [1]. Therefore, only one laser beam and one photodiode positioned in the axis of the laser beam are necessary. That allows a lance-shaped realization of the SE-Sensor which can be used in spray towers. For measurements conducted in one plane only one notch with a diameter of about 50 mm in the outer wall of the tower is necessary to feed the lance into the tower. Another advantage of this measuring principle over scattered light measurement systems is that shadowing effects of droplets are less dependent on the optical properties of the droplet compounds than scattering effects

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[2]. Measurements with very high droplet concentrations and measurements at different positions in the spray tower are possible with the sheath-extinction method invented by Steinke [3]. Axially displaceable sheaths are used to protect the laser beam for a variable length against spray influence. However, this is not possible with existing measurement techniques. The measuring volume in the tower can be moved at any place within the spray, which allows to investigate the spray profile within the spray tower.

The inline measurement of a mean droplet diameter is adequate to realize an inline process control. To improve the understanding of spray processes the SE-Sensor has to be upgraded to provide the measurement of droplet size distributions. The objectivity of this study is to examine, if the measurement of the extinction of nine laser beams with different laser beam diameters provides the calculation of particle size distributions (PSD). Therefore a new sensor with nine laser beams with different beam diameters (subsequently referred as to PSD-SE-Sensor) is constructed.

Statistical Extinction Method

The measuring system calculates the droplet size and their concentration from the extinction of a laser beam, which illuminates a well-defined volume of the spray. The Lambert-Beer law provides the interrelationship between the extinction $E(x,c_N,\lambda,m)$ of the laser beam and the droplet size x plus their number concentration c_N in the spray [4], [5]:

$$E(x,c_N,\lambda,m) = -ln(T) = -ln\left(\frac{I}{I_c}\right) = c_N \cdot C_{ext}(x,\lambda,m) \cdot L \tag{1}$$

The extinction results from the transmission T, which is measured by the detection of light intensities I and I_c. I_c is the intensity of the laser beam behind the measuring volume which is filled exclusively with continuous phase. I is equivalent to the intensity of the extinguished laser beam behind the measuring volume which is filled with disperse and continuous phase. C_{ext} is the extinction cross section of a droplet with a diameter x depending on the wavelength λ of the laser and the refractive index ratio m between disperse and continuous phase. c_N is the number concentration of the droplets in the spray. L is the length of the measuring volume.

Equation (1) includes two independent characteristic spray sizes (x and c_N), so that a second, independent measuring value is required. The statistical extinction method uses the root mean square deviation of fluctuating transmission signals σ_T. The root mean square deviation can simply be calculated from the measured values of the transmission T. The additional information results from the fact, that bigger droplets which enter or leave the measuring volume cause a larger fluctuation in the extinction signal than smaller droplets. According to Gregory [1] the mean extinction cross section of the droplets of a spray depends on the mean values of the measured transmissions and their root mean square deviations as follows:

$$\overline{C_{ext}(x,\lambda,m)} = -\frac{A_{meas}}{ln(\overline{T})}\left[ln\left(\frac{\sigma_T}{\overline{T}} + \sqrt{\left(\frac{\sigma_T}{\overline{T}}\right)^2 + 1}\right)\right]^2 = k_{ext}(x,\lambda,m) \cdot \frac{\pi}{4} x^2 \tag{2}$$

A_{meas} is the mean cross section of the laser beam in the measuring volume (subsequently referred as to measuring cross section). The extinction cross section C_{ext} can be expressed by the product of the extinction coefficient k_{ext} and the projected droplet cross section area. The extinction coefficients are calculated according to the Bohren-Huffmann algorithm [6]. The product of the extinction coefficient k_{ext}, which depends on the droplet size x, and the projected droplet cross section area cannot be solved explicitly for the droplet size. Therefore it is necessary to calculate these values for a series of droplet sizes and tabulate them depending on the droplet size. Thus, the droplet size can be calculated by a linear interpolation of the measured extinction cross section.

The number concentration of droplets results from the droplet size computed by equation (2) and the measured value of transmission T by solving equation (1) for the number concentration. The droplet volume concentration c_V is computed by multiplying the number concentration c_N with the mean droplet volume.

There are some effects which influence the transmission signal and thereby the computation of the extinction cross section C_{ext} according to equation (1) and (2). Therefore, these effects need to be taken into account by the measurement data processing.

Droplets which are positioned at locations that are already partially shaded by other droplets cause a reduced shading effect, so that the measured size of these droplets is smaller than the actual size. This effect has a wide influence if the droplet-volume-concentration c_V is larger than 20 %. Boundary-layer-effects influence the measured transmission values, too, especially for droplets with extinction cross sections C_{ext} larger than the measuring cross section A_{meas}. The aperture angle of the measuring system influences measured extinction cross sections C_{ext} because a part of the light intensity which is scattered by droplets is detected by the diode. This part of the light intensity is also interpreted as transmission. All these effects are taken into account by calculating the droplet diameters. [7] [8]

Equation (1) and (2) are strictly valid only for monodisperse systems. For polydisperse systems only a mean value of the droplet size can be measured. According to Kerker [9] and Dobbins and Jizmagian [10] equation (1) can be modified, so that it is valid for a wide variety of monomodal size distributions. In this case the mean diameter of the droplets is close to the Sauter mean diameter $x_{3,2}$. The Sauter mean diameter is the diameter of a sphere, which has the same volume to surface ratio as the disperse system. But equation (1) is only used to calculate the droplet concentration c_N from the measured transmission T and the mean droplet size, which is calculated by equation (2).

For equation (2) the authors are not in knowledge of a universally valid modification for polydisperse systems. Gregory [1] describes one possible modification, which requires that the droplet size is logarithmic normally distributed and the root mean square deviation of the droplet size distribution is known. But this information is not available for usual spray processes. Additionally, the polydispersity of the spray influences the root mean square deviation of the transmission T. The mean size of the droplets which are positioned in the laser beam is temporarily fluctuating. This causes an additional root mean square deviation of the transmission T [2]. For larger root mean square deviations of the transmission T, equation (2) gives larger mean droplet diameters. Therefore wider droplet size distributions cause larger calculated mean droplet diameters.

To take this effect into account by the calculation of the mean droplet size, a measuring cross section $A_{meas,emp}$ is determined empirically. Therefore different sprays are analyzed by a laser diffraction system called Spraytec from Malvern Instruments. The droplet size distributions and some mean values of the droplet size (mass median diameter x_{50}, arithmetic mean diameter x_m, Sauter mean diameter $x_{3,2}$) are determined. The same sprays are analyzed by the SE-Sensor. Equation (2) is solved for the measuring cross section A_{meas}. For the mean droplet diameter x in equation (2), the values of one of the mean diameters which are determined by the Spraytec are used. The kind of mean value of the droplet size which is used to calculate the empirical measuring cross section $A_{meas,emp}$ will be determined as mean droplet size by the statistical extinction sensor. For spray processes the volume to surface ratio is an important characteristic value. Therefore the Sauter mean diameter $x_{3,2}$ is used to determine the empirical root mean square deviation $A_{meas,emp}$. [11]

The described SE-Sensor measures a mean droplet diameter and the concentration of the droplets. To measure droplet size distributions more independent measurement values have to be detected. The number of the detected measurement values has to be as large as the number of the size ranges of the size distribution, which shall be determined. The effective extinction cross section $C_{ext,eff}$ of a droplet in the measuring volume depends on the ratio of the droplet cross section C_{ext} to the measuring cross section A_{meas}. Fig. 1 shows three blue droplets with identic diameters which extincts three red laser beams with different diameters. Below these droplets the maximum extinction cross sections $C_{ext,max}$ which can be caused by the droplets are displayed. If the droplet diameter is larger than the laser beam diameter, the maximum extinction cross section $C_{ext,max}$ is as large as the measuring cross section A_{meas}. If the droplet diameter is smaller than the laser beam diameter, the maximum extinction cross section $C_{ext,max}$ is as large as the extinction cross section of the droplet C_{ext}.

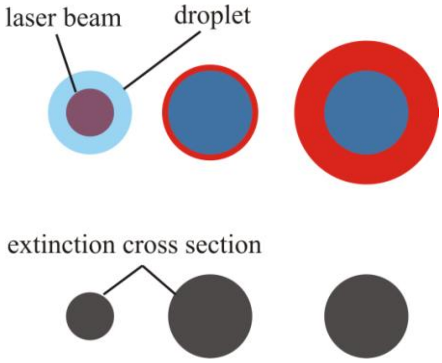

Fig. 1 Influence of the measuring cross section on the projected extinction cross section of a droplet.

Extinction cross sections which are determined by real measurements are usually smaller than the maximum extinction cross sections $C_{ext,max}$ which are shown in Fig. 1. This is caused by the effects named above which influences the measured transmission T. These effects are taken into account by the calculation of the extinction coefficients [7].

The measured mean extinction cross section $C_{ext,meas}(A_{meas})$ of a polydisperse particle system can be calculated from the quantity distribution $q_0(x)$ and the theoretical extinction cross section $C_{ext,theo}(A_{meas},x)$, which depends on the measuring cross section A_{meas} and the droplet size x. If the extinction cross section C_{ext} of a droplet is smaller than the measuring cross section $A_{meas,i}$, the theoretical extinction cross section $C_{ext,theo}(A_{meas},x)$ is equal to the extinction cross section C_{ext} of the droplet. If the extinction cross section C_{ext} of a droplet is larger than the measuring cross section $A_{meas,i}$, the theoretical extinction cross section $C_{ext,theo}(A_{meas},x)$ is equal to the measuring cross section $A_{meas,i}$ of the laser beam i.

$$C_{ext,meas}(A_{meas}) = \int_{x_{min}}^{x_{max}} q_o(x)\cdot C_{ext,theo}(A_{meas},x)\,dx \tag{3}$$

The kind of equation (3) is equivalent to an alpha type of a Fredholm integral equation. To solve equations of this type special algorithms are available [2]. One of them is discussed later.

The discretization of equation (3) gives a linear system of *i* equations as shown in equation (4).

$$C_{ext,meas}(A_{meas,i}) = \sum_{j} \Delta Q_o(x_j)\cdot C_{ext,theo}(A_{meas,i},x_i) \tag{4}$$

The extinction cross sections $C_{ext,meas}(A_{meas,i})$ which are measured with different measuring cross sections $A_{meas,i}$ build the vector of results *R* of the equation system. The theoretical extinction cross sections $C_{ext,theo}(A_{meas},x)$ build the coefficient matrix *C*. The vector which solves the equation system *S* is composed of the discretizised quantity concentration $\Delta Q_0(x_j)$. Thus, equation (4) can be written as follows:

$$R = C\cdot S \tag{5}$$

The exact solution of equation (5) is the linear inversion of the equation by multiplying both sides of the equation by the inverted coefficient matrix C^{-1} from the left side.

$$S = C^{-1}\cdot R \tag{6}$$

But this solution is very prone to measurement faults. Fig. 2 shows, that already random faults of the result vector *R* of f = 0.5 % cause unusable calculated quantity distributions. The calculated distribution includes unfeasible negative values and shoes significant deviations from the quantity distribution which is calculated without any faults of the result vector *R* (default).

There are a few methods to solve Fredholm integral equations which are not that prone to measurement faults [2], [12]. One of them is the inversion with linear smoothing according to Phillips-Twomey, which is used, for example, to analyze the measuring data of laser diffraction systems. To solve equation (6) by this method, the inverted coefficient matrix C^{-1} is multiplied by the inverted transformed coefficient matrix $(C^T)^{-1}$ from the left side and with the transformed matrix C^T from the right side.

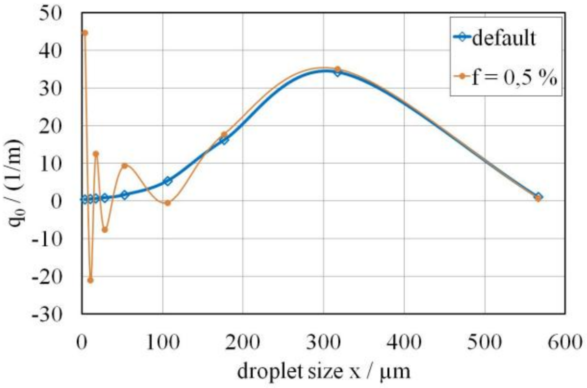

Fig. 2 Influence of random faults of the result vector of 0.5 % on the quantity distribution calculated by linear inversion of the equation system.

$$S = C^{-1}\cdot R = \left(C^T\cdot C\right)^{-1}\cdot C^T\cdot R \tag{7}$$

In this form of equation (6) a smoothing term can be added to the coefficient matrix. This term consist of a smoothing matrix *G* and a smoothing factor *g*. To get a smooth run of the number distribution a unit matrix is used as smoothing matrix.

$$S = \left(C^T\cdot C + g\cdot G\right)^{-1}\cdot C^T\cdot R \tag{8}$$

The optimal value of the smoothing factor *g* depends on the mean value of the measurement faults *f*. Fig. 3 shows quantity distributions which are calculated from a result vector *R* with random faults with a mean value of *f* = 1 % by using different smoothing factors *g* from 0.001 to 1.000. If the smoothing factor is chosen too small (*g* = 0.001), the calculated quantity distribution shows too large oscillations and significant deviations from the quantity distribution which is calculated without any faults of the result vector. If the smoothing factor is chosen too large (*g* = 1.000), the quantity distribution function is calculated to flat and too smooth.

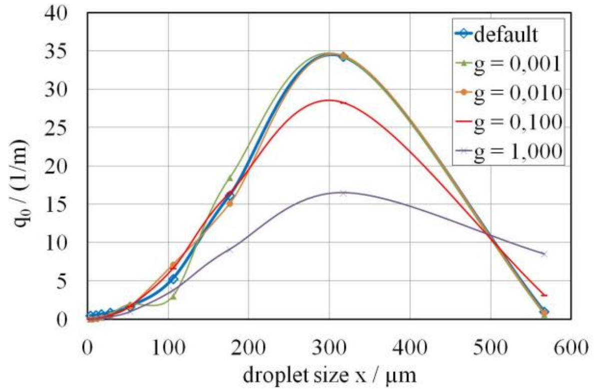

Fig. 3 Influence of the smoothing factor *g* on the calculation of quantity distributions which result from result vectors with random faults with a mean value of *f* = 1 %.

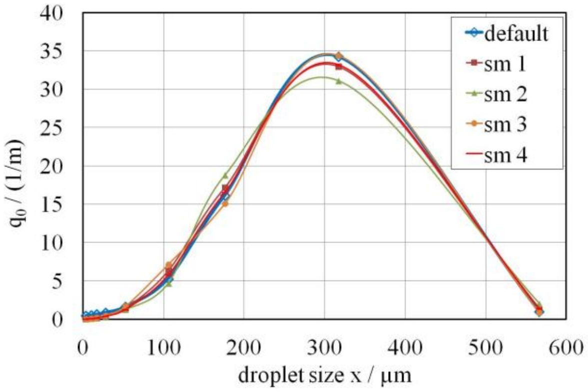

Fig. 4 Quantity distributions calculated with random faults with a mean value of *f* = 1 % of the results vector (smoothing factor *g* = 0.01) compared to the size distribution (default) calculated without faults of the results vector (smoothing factor 0).

If the smoothing factor matches the result vector *R* (*g* = 0.01 for *f* = 1 %), the quantity distribution calculated by linear smoothed inversion matches the default distribution (*g* = 0, *f* = 0). Fig. 4 shows this for quantity distributions calculated from four result vectors with different random faults with a mean value of *f* = 1 % by using a smoothing factor of *g* = 0.01.

Fig. 5 illustrates the influence of the mean value of the random fault *f* of the result vector *R* on the calculated quantity distributions by using the optimal smoothing factor *g* for each value of the mean value of the random fault *f*. With random faults of *f* = 1 % (*g* = 0.01) the quantity distribution is calculated without significant deviations to the default distribution (*f* = 0 %, *g* = 0). With random faults with a mean value up to *f* = 5 % quantity distributions can be calculated with acceptable deviations to the default distribution. With a mean value of the random faults of *f* = 10 % the method is not suitable to calculate usable quantity distributions.

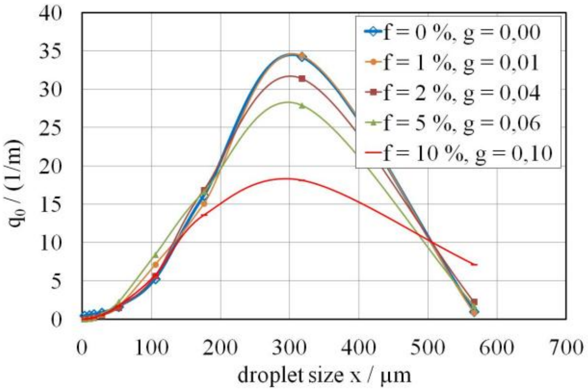

Fig. 5 Influence of random faults of the result vector R on the calculated quantity distribution by using an optimal smoothing factor.

Sensor Design

The layout of the SE-Sensor is illustrated in Fig. 6. A diode laser generates a laser beam with a wavelength of 659 nm. A fibre optic transmits the laser beam to a beam splitter which divides the laser beam into two parts. One laser beam with 1 % of the light intensity is transmitted by a fibre optic to a collimator which collimates the laser beam on a photodiode. This diode (hereinafter referred to as reference diode) measures the intensity of the laser beam. The other laser beam with 99 % of the light intensity is transmitted by another fibre optic to a second collimator which collimates the laser beam in the spray. The form of the light intensity distribution of this laser beam equates to a Gaussian normal distribution curve. The 1/e² diameter of this laser beam is 2.9 mm. In the measuring volume a part of the laser intensity is extincted by the droplets of the spray. The rest of the laser beam is reduced to a defined diameter by a pinhole, which is positioned behind the measuring volume. The pinhole can be replaced easily, so that pinholes with different diameters from 10 µm to 1000 µm can be used. A photodiode which is positioned behind the pinhole measures the intensity of the extincted laser beam (hereinafter referred to as main diode). In Fig. 6 this main diode is displayed at the rightmost position. The 1/e² diameter of the laser beam is much larger than the diameter of the pinholes so that the pinholes are illuminated with a nearly constant intensity. The diameter of the part of the laser beam which is extincted by the spray and detected by the main diode is nearly constant for the whole measuring length and equal to the pinhole diameter. The diffracted part of the laser beam which enters the sheaths is absorbed by a black matt paint at the inside of the sheaths. To guarantee that the part of the laser beam which is diffracted by the pinhole is detected by the main diode, the photodiode is positioned directly behind the pinhole.

The measuring volume, in which the laser beam is extincted by the spray, is positioned between the two sheaths. These sheaths protect the collimator and the main diode against fouling and limit the measuring volume to a defined path length L. A small airflow, which flows through the sheaths in the direction of the measuring volume, prevents the penetration of droplets and particles into the sheaths and can provide cooling effects. This enables the application of the sensor in high temperature processes.

The measuring volume can be moved in the direction of the laser beam by moving the sheaths for an identical distance in this direction. Hence the spray can be investigated spatially resolved at any place. The length of the measuring volume can be changed by moving the sheaths. With a variable length of the measuring volume measurements in the optimum transmission range from 20 % to 80 % are possible with different concentrations of the disperse phase. [3]

To determine the transmission of the laser beam through the spray the intensity of the laser beam which is extincted by a measuring volume filled with continuous and disperse phase (I) has to be measured as well as the intensity of the laser beam which is extincted only by continuous phase (I_c). Because light intensity emitted by the laser diode is temporarily not constant, both values have to be measured simultaneously. The intensity behind the measuring volume filled with disperse and continuous phase is measured by the main diode. The intensity behind the measuring volume filled exclusively with continuous phase is measured by the reference diode. Before sprays can be measured, the measurement system has to be calibrated, so that the reference diode measures the intensity I_c. [11]

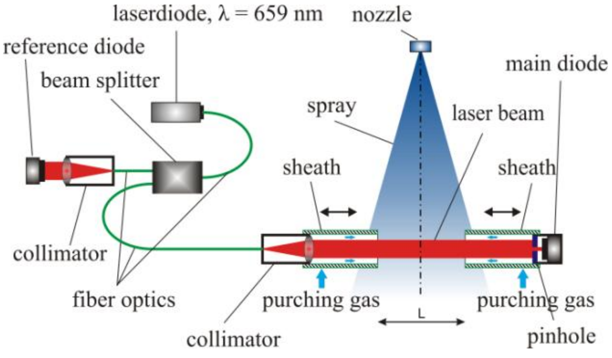

Fig. 6 Principle sketch of the SE-Sensor.

To measure particle size distributions (PSD) the PSD-SE-Sensor is constructed. The pinhole is replaced by a pinhole with nine holes with different diameters from 10 µm to 1000 µm. The main diode is replaced by an array of nine main diodes, which are positioned behind the nine pinholes. The measurement principle assumes that the nine laser beams are extincted by the same part of the spray. To fulfil this requirement, the pinhole with nine holes has a maximum width of 6 mm. This pinhole has to be illuminated with a nearly constant light intensity distribution which requires a laser beam with a 1/e² diameter of 20 mm. This is realized by substituting the collimator which generates the measuring laser beam.

Fig. 7 displays two different concepts to implement a SE-Sensor in a drying tower. The left side shows a one-piece sensor concept in which the emitter and the detector are positioned on one optical axis in the drying tower. The laserdiode, the beam splitter and the reference diode are positioned outside the drying tower. The laser beam is transmitted into the tower to the emitter of the sensor by a fibre optic. The sensor is conctructed lanceolate to minimize the manipolation of the spray in the tower by the sensor. The outer width of the lance is 36 mm, the hight is 50 mm. The right side shows a two-piece concept, in which the emitter and the detector are positioned behind two opposite notches outside the drying tower. The usage of the shaths is optional. If the sheaths are used, they limit the measuring volume to a defined path length. If the sheaths are not used, there are no componets inside the drying tower which can influence the spray. In this case, the purging gas flows from the box around the emitter/detector unit through the notch in the outer wall of the tower into the tower. Thus, it prevents the penetration of droplets and particles into the boxes and protects the collimator and the main diode against fouling.

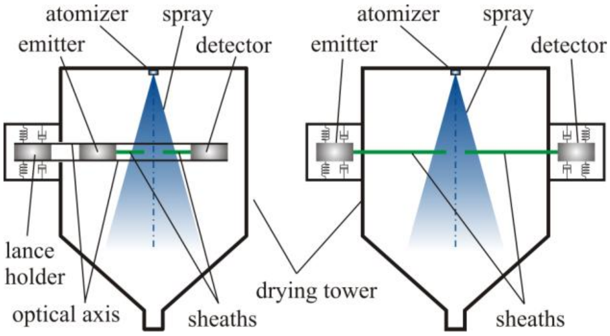

Fig. 7 Different concepts to implement the SE-Sensor in a drying tower. Left side: One-piece lanceolate concept. Right side: Two-piece concept.

The PSD-SE-Sensor can only be realized with the two-piece concept (Fig. 7, right side) because the collimator which generates a 1/e² laser beam diameter of 20 mm has an outer diameter of 58 mm. This is too large for a lanceolate realization of the sensor.

Results and Discussion

To validate the measurement capability of the SE-Sensor different sprays are analyzed by the SE-Sensor. The sprays are generated with a one phase nozzle of type 460.403 from Lechler company with atomizing pressures from 2 bar up to 11 bar. The atomized phase consists of water. The mean droplet sizes measured by the SE-Sensor are compared to different mean droplet sizes determined by a laser diffraction system called Spraytec from Malvern Instruments. The Spraytec measures droplet size distributions, so that the different mean values determined by the Spraytec (mass median diameter x_{50}, arithmetic mean diameter x_m, Sauter mean diameter $x_{3,2}$) are calculated from one measurement data. [11]

The PSD-SE-Sensor determines a mean extinction cross section size with each laser beam. From the mean extinction cross section a mean droplet size can be calculated. Fig. 8 shows mean droplet sizes measured by the SE-Sensor with a pinhole diameter of 600 µm. The green displayed values are calculated with the theoretical measuring cross section. The same sprays are analyzed with the Spraytec. The mean values of the statistical extinction sensor are smaller than all mean diameters which are determined with the Spraytec. This is caused by the diameter of the laser beam which is smaller than the large droplets of the spray. Therefore these droplets are measured too small which causes the smaller mean diameter. Another effect which influences the measuring results of the statistical extinction sensor is the polydispersity of the sprays. This effect causes an additional root mean square deviation of the transmission *T*. The droplets are measured too large. But this effect is not big enough to compensate the effect discussed above.

To measure a mean diameter of the sprays with the SE-Sensor an empirical extinction cross section $A_{meas,emp}$ is determined as discussed above. Therefore equation (2) is solved for the measuring cross section A_{meas}. To describe spray drying processes the Sauter mean diameter $x_{3,2}$ is appropriate mostly, so that the Sauter mean diameter measured with the Spraytec is used as mean droplet size.

The mean values of the droplet diameter which are displayed with red colour in Fig. 8 are calculated by using the empirical measuring cross section $A_{meas,emp}$. These values show a good accordance to the values of the Sauter mean diameter $x_{3,2}$ which were measured with the Spraytec. Measurements of sprays generated with other nozzles corroborate this [11]. Thus the SE-Sensor is able to measure a mean droplet diameter which is close to the Sauter mean diameter by using the empirical extinction cross section $A_{meas,emp}$.

To determine droplet size distributions the transmission of nine laser beams with different diameters has to be measured. Fig. 9 displays mean droplet sizes of sprays generated by the Lechler 460.403 which are measured with the PSD-SE-Sensor by using the theoretical measuring cross sections $A_{meas,theo}$. Smaller diameters of the laser beam cause smaller measured mean droplet sizes. This matches the theory which is discussed above.

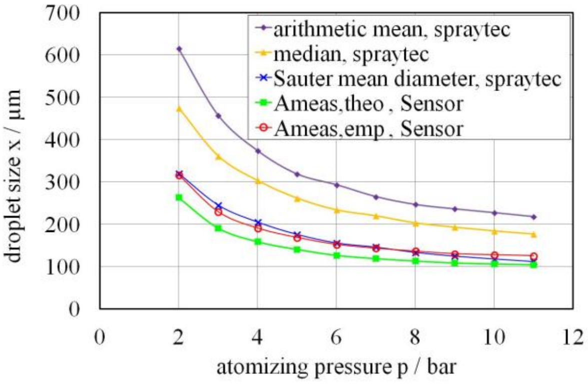

Fig. 8 Different mean droplet sizes determined with the Spraytec compared to two mean droplet size measured by the statistical extinction sensor by using the theoretical and the empirical measuring cross section.

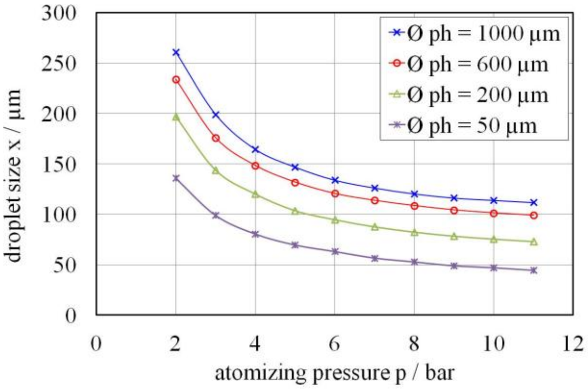

Fig. 9 Mean droplet sizes measured with the statistical extinction sensor by four laser beams with different diameters of the measuring cross section.

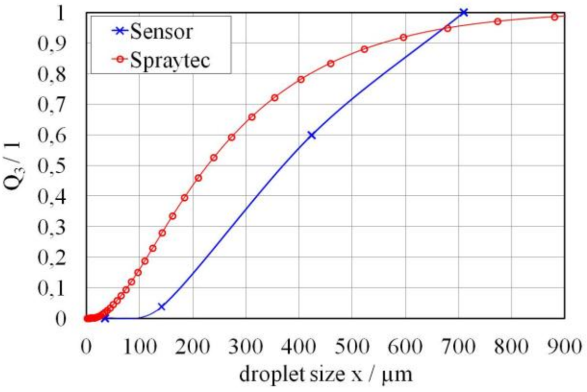

Fig. 10 Droplet size distribution measured by the statistical extinction sensor and the Spraytec (Lechler 460.403, atomizing pressure 7 bar)

The droplet size distribution of a spray can be calculated with equation (8). Fig. 10 shows the cumulative droplet size distribution of a spray of the Lechler

460.403 generated with an atomizing pressure of 7 bar. The values which are displayed with red colour are measured with the Spraytec. The blue displayed values are measured with the PSD-SE-Sensor with four laser beams with beam diameters of 50 µm, 200 µm, 600 µm, and 1000 µm. The values of the measured extinction cross sections $C_{ext,meas}(A_{meas,i})$ are used as result Vector *R*. The coefficient matrix is defined as discussed above. To get a smooth run of the number distribution a unit matrix is used as smoothing matrix. A value of 0,005 is used as smoothing factor *g*.

The cumulative droplet size distribution measured with the PSD-SE-Sensor shows a smooth run of curve whose slope is similar to the cumulative droplet size distribution which is measured with the Spraytec. But the size distribution measured with the PSD-SE-Sensor shows larger droplet sizes than the Spraytec. That is caused by the polydispersity effect which is discussed above.

Therefore the calculation of the droplet size distribution will be optimized by using an iterative method. First, a cumulative droplet size distribution is calculated. From this size distribution the width of the size distribution is calculated. With this information a droplet size distribution is calculated by correcting the effect of the polydispersity of the calculated width. From this size distribution a corrected width of the distribution is calculated. First results of this calculation method will be shown in a subsequently paper.

Summary and Conclusions

The SE-Sensor provides the inline measurement of a mean droplet diameter in drying towers. To measure droplet size distributions of process sprays inline in drying towers, the PSD-SE-Sensor is constructed. It includes nine laser beams with nine different beam diameters to illuminate the spray. The extinction values of the laser beams are detected by nine main diodes. Because the measuring principle requires that all laser beams are extincted by the same part of the spray, only one laser beam with a diameter of 20 mm illuminates the spray. The nine different laser beam diameters are defined by a pinhole with nine holes with different diameters which is positioned behind the measuring volume. This guaranties well defined laser beam diameters. The droplet size distribution is calculated from equation (8), which has the form of a Fredholm integral equation. To solve this equation, a linear smoothed inversion of equation (8) is used, because this method is less prone against random measurement faults.

First droplet size distributions measured with the PSD-SE-Sensor show larger droplet sizes than the droplet size distributions measured with a Spraytec. This is caused by the effect of the polydispersity of the sprays on the root mean square deviation of the transmission of the laser beams. A calculation method which takes this effect into account will be shown in a subsequently paper.

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