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Automated drop detection using image analysis for online particle size monitoring in multiphase systems

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ABSTRACT

Image analysis has become a powerful tool for the work with particulate systems, occurring in chemical engineering. A major challenge is still the excessive manual work load which comes with such applications. Additionally manual quantification also generates bias by different observers, as shown in this study. Therefore a full automation of those systems is desirable. A MATLAB® based image recognition algorithm has been implemented to automatically count and measure particles in multiphase systems.

A given image series is pre-filtered to minimize misleading information. The subsequent particle recognition consists of three steps: pattern recognition by correlating the pre-filtered images with search patterns, pre-selection of plausible drops and the classification of these plausible drops by examining corresponding edges individually. The software employs a normalized cross correlation procedure algorithm. The program has reached hit rates of 95% with an error quotient under 1% and a detection rate of 250 particles per minute depending on the system.

1. Introduction

The competitive pressure in the chemical industry makes it necessary to take measures that enable processes to be drastically improved in order to remain competitive also in the future (Ruscitti et al., 2008). Product quality control is more complex in particulate than in conventional chemical processes. The key properties of the product are often related to the particle size distribution (PSD) which is influenced by the operating conditions and the history of the process (Zeaiter, Romagnoli, & Gomes, 2006). Disturbances in operating conditions may irreversibly change the quality of the product. Quantitative real-time measuring is needed to enable feedback control. Monitoring and control of such processes have evoked interest in the use of image-based approaches to estimate product quality in real time and in situ (Zhou, Srinivasan, & Lakshminarayanan, 2009).

During the last decades extensive research has been performed to establish and improve technologies which measure particle properties, such as size, shape, composition, and velocity. Concerning the interpretation of particle size distributions using different physical principles there is still a considerable lack of understanding (Leschonski, 1986).

Various authors found unsatisfying results, analyzing spherical drops in different liquid/liquid systems, using laser optical measurement techniques based on back scattering (Boxall, Koh, Sloan, Sum, & Wu, 2010; Greaves et al., 2008; Honkanen, Eloranta, & Saarenrinne, 2010; Maaß, Wollny, Voigt, & Kraume, 2011). These authors are questioning the reliability of these online probes in general and reaffirming the need to use image analysis (IA) instead as the particle surface unpredictably influences the signals.

A further limitation, according to different authors (Martínez-Bazán, Montanés, & Lasheras, 1999; Niknafs, Spyropoulos, & Norton, 2011; Pacek, Moore, Nienow, & Calabrese, 1994), is the use of external physical sampling. This never can guarantee that the particle size does not change during measuring. Even for sampling times less than a second, significant measurement errors can occur. In order to get reliable drop size distribution (DSD) measurements the technique needs to be chosen carefully. This work is focused on a MATLAB® based image recognition algorithm, which is able to automatically measure particles robust in different multiphase systems.

The paper is structured as follows. The use of image analysis for sizing fluid particles is shortly reviewed in Section 2 followed by an introduction of the used experimental set-ups in Section 3. Image pre-processing and image analysis size measurements are given in Sections 4 and 5. The results achieved by that method are compared with manual results in Section 6.

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Nomenclature

Symbols

B_i	individual original picture
$\hat{B'}_i$	processed image
b_j	average gray value
d_{32}	Sauter mean diameter (m)
D	stirrer diameter (m)
d	Euclidean distance (pixel)
H	liquid level height (m)
K	convolution core
n	number of particles (#)
n	refraction index (–)
n_B	number of images in one batch (–)
q_0	number density distribution (1/m)
Q	self quotient image
Q_0	cumulative number distribution (–)
R_j	absolute radius of an individual particle (m)
r	control variable
S	cumulative average image from a whole sequence
$\overline{S}$	average pixel value of S
s	stirrer distance (m)
T	pattern
T	vessel diameter (m)
$\overline{T}_{u,v}$	average gray value from the according pattern
V	result for NCC
X	convoluted image
α	angle (°)
φ	dispersed phase fraction (–)

Abbreviations

CP	correlation procedure
NCC	normalized cross correlation

2. Image analysis in multiphase systems

Although process characterization based on image analysis (IA) can be intensely time consuming, it needs to be applied to almost every dry and wet particulate system. A short summary of published applications in liquid systems is given by Guevara-López et al. (2008) and for dry systems by Andrès, Réginault, Rochat, Chaillot, and Pourcelot (1996). Emerging applications show that utilization of image analysis can facilitate the creation of new and sophisticated models for the control of particulate systems (Williams & Jia, 2003). In this paper we only focus on the characterization of the size of particles based on IA.

The most extensive available review on this specific field is given by Junker (2006). A detailed description of the technical and historical developments can be found there. This review also shows that the photo-optical in situ measurement of particle sizes in multiphase systems is already well established. Many applications have been reported in literature with different set-ups (Aakre, Solbakken, & Schüller, 2005; Alban, Sajjadi, & Yianneskis, 2004; Fantini, Tognotti, & Tonazzini, 1990; Galindo et al., 2005; Hossain, Yang, Borgna, & Lau, 2011; Junker, Maciejak, Darnell, Lester, & Pollack, 2007; Kamel, Akashah, Leeri, & Fahim, 1987; Khalil et al., 2010; Mickler, Didas, Jaradat, Attarakih, & Bart, 2011; O'Rourke & MacLoughlin, 2005; Roitberg, Shemer, & Barnea, 2006; Torabi, Sayad, & Balke, 2005), all of which worked well for the applications investigated. They are based on digital, high-speed, high resolution modular camera systems and the images are analyzed with commercial or self developed image analysis software and standard statistical methods.

Junker (2006) gives an organized overview of the applied photographic techniques used in literature. They stated that CCD-cameras are the optimum for the effort/cost ratio. Fig. 1 shows an example image gallery from such a standard camera. Pictures are taken at a maximum frequency of 50 frames per second with this technique which is equal to a recording time, also called data acquisition time (DAT) of 1/50 s per image. Already Leschonski (1986) and also Junker (2006) emphasize the necessity of short DAT and additionally a short measurement acquisition time (MAT). The MAT is the DAT plus the time needed to extract the necessary information from a sample image and translate this information into the particle size distribution. Ideally the MAT equals the DAT (Crawley & Malcolmson, 2004).

To get statistically reliable data sets 100s or 1000s of particles have to be measured. Particle systems are very different and so are the number of particles on one image (see Fig. 1) and therewith the number of frames required for a single measurement. A minimum of 250 drops need to be captured within some seconds to achieve real time DAT. Junker (2006) reports in her studies a variation between 2 and 400 frames. The required number of objects per measurement becomes important for storage reasons, if all images need to be reviewed and therefore saved. This problem should become less and less significant with the ongoing developments of computer hardware.

Usually for drop sizing applications the MAT (5–60 min) is much greater than the DAT (Junker, 2006). These time ranges are unsuitable for process monitoring and control. The manual evaluation of such images is highly time-consuming and therefore automation of image analysis should be employed to speed up the MAT at least one to two magnitudes. Another disadvantage of manual evaluation was firstly reported by Gwyn, Crosby, and Marshall (1965). Due to the subjective nature of manual particle counting the measured distributions are human biased. The significant statistical variations mostly occur especially at the "tails" of the distributions. Boxall et al. (2010) also showed the influence of human bias with an average difference of 5.1% in the average drop size for two different analyzers. Automated quantification would avoid bias by different observers.

Simplified image analysis for the discussed multiphase systems can be achieved by using only low dispersed phase fractions in which no overlapping occurs. Several examples for this approach are reported in literature (Khalil et al., 2010; Mickler et al., 2011; Scherze, Knofel, & Muschiolik, 2005). These successful implementations of image analysis algorithms all fail for highly concentrated (phase fraction larger than 10–15%) dispersions. Additionally no commercial software for the analysis of such systems, which would be needed for industrial relevant applications is currently available (Brás, Gomes, Ribeiro, & Guimarães, 2009). More promising are the works of Alban et al. (2004) and Brás et al. (2009).

The image analysis technique employed by Alban et al. (2004) includes several steps of arc and circle center detection and pattern matching. The number of particles detected in the image depends on the image quality. Detection levels vary from 10 to 90%. Large particles are accurately detected even when they are obstructed by smaller particles. Errors in detection occur especially for very small particle sizes when thick particle peripheries are present. This does not significantly affect the used Sauter mean diameter ($d_{32} = \sum d_i^3 / \sum d_i^2$), due to emphasis of large particles in this calculation. Brás et al. (2009) are using a two step approach that automatically identifies the contour of existing drops and classifies them according to their diameter. In the first step, they detect the edges of the drops in the original image by monitoring the values of the image gray values as well as the descending thickness and by creating an output image with those contours. In the second phase, they detect the drops in this contour image, using the Hough transformation (Cohen & Toussaint, 1977) to evaluate the circles.