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An automated image analysing routine for estimation of equivalent diameter in high-speed image sequences with high accuracy and its validation

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ABSTRACT

Bubbly flow plays an important role in industrial processes. Obtaining detailed information on the flow is, however, a challenging task. One of the key process parameters is the diameter of the bubbles, which is often determined as equivalent diameter. In this study, an automatic image analysis routine for time-resolved analysis and estimation of equivalent diameter of rising single bubbles in high-speed image sequences with high accuracy is developed using the open source software KNIME. Common estimation techniques for the equivalent diameter, e.g. based on the major/minor axes, are compared to a novel rotation algorithm, where the detected bubble segments are rotated by 180° in 1° steps, for the determination of the Feret diameter. Additionally, the elongation is measured as a morphological parameter and the centroid positions are determined. In combination with the frame rate of the image sequences the ascent rates can be calculated in form of a Bubble Tracking Velocimetry (BTV). The routine was validated using static computer generated geometrical shapes as well as precision grade solid glass spheres with diameters of 0.7–2.5 mm under dynamic (settling) conditions. High-speed image sequences were recorded and analysed with a critical statistical evaluation. It could be shown that the deviation between measured diameter and real diameter of the glass spheres is less than 1.5% when using the rotating Feret diameter algorithm. Settling velocities were determined with a maximum error of 3%. A first test of the analysing routine in a bubbly flow showed that it is unaffected by dirt, small tracer particles or internals in the viewing area, which makes a combined Particle Image Velocimetry (PIV) and Shadowgraphy analysis feasible.

1. Introduction

Multiphase flow has a broad range of applications in the chemical industry. Two phase gas-liquid flows are commonly used, e.g. in bubble columns or in flotation processes. In both applications, the diameter of the bubbles is of particular interest. In bubble columns, it is a limiting factor for mass transfer [1]. In the flotation process, the bubble size has a significant influence on the separation efficiency [2].

Due to technological developments in the recent years, online characterization systems for multiphase flows have gained a greater interest. There are several bubble sizing approaches described in literature, e.g. electroresistivity [3], ultrasound [4,5] and optical methods [6]. Latter are divided into different methods, such as using optical fibres [7,8], isokinetic collection probe [9] and imaging techniques. Due to their easy implementation, imaging techniques are widely used. A common technique is the Shadowgraphy, where the multiphase flow is filmed with a high-speed camera, which captures image sequences. A backlight is used to illuminate the flow. The bubbles appear as a shadow in the image sequences with a bright background and can thus be easily analysed. Many different apparatuses were presented in literature, e.g. the McGill bubble size analyser [10], the Helsinki University of Technology (HUT) bubble size sampler [11] and the Laboratório de Tecnologia Mineral e Ambiental Bubble Sizer (LTM-BSizer) [12]. All of the used techniques have in common that they function as samplers, where a small fraction of the bubbly flow enters a viewing chamber. In this chamber, high-speed image sequences of the rising bubbles are recorded. Automatic image analysis is a key process for the evaluation of these image sequences. In industrial processes it is often used as quality assurance, e.g. for food products [13,14]. In complex flotation processes the froth appearance and structure is often used as quality indicator [15–17]. There are a lot of commercial programs for image analysis available, e.g. DaVis by LaVision [18], or DynamicStudio by Dantec Dynamics [19]. Many commercial programs like Matlab have integrated image-analysis plug-ins, which may be used for this purpose, too. Open source programs have, in contrast to these, the great advantage that they allow complete modification of the

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Nomenclature

Ar_P	particle Archimedes number, dimensionless
C	centroids coordinates in x and y direction
C_D	drag coefficient, dimensionless
CMOS	complementary metal-oxide-semiconductor
d_{eq}	equivalent diameter based on the major and minor axes (m)
$d_{eq,F}$	equivalent Feret diameter (m)
d_{major}	major axis (m)
d_{max}	maximum diameter (m)
d_{min}	minimum diameter (m)
d_{minor}	minor axis (m)
d_P	particle diameter (m)
DoF	depth of field
e	shape descriptor eccentricity, dimensionless
f_{elong}	shape descriptor elongation, dimensionless
fps	frames per second (s^{-1})
g	acceleration due to gravity ($m\,s^{-2}$)
KNIME	Konstanz information miner
l	lower
LED	light-emitting diode
r	critical parameter for Dixon's Q test
RGB	colour model based on red, green and blue
Re_P	particle Reynolds number, dimensionless
t	time (s)
u	upper
v	ascent rate ($m\,s^{-1}$)
v_s	settling velocity ($m\,s^{-1}$)
x	position of the centroid in x direction (m)
y	position of the centroid in y direction (m)
ϱ_F	fluid density ($kg\,m^{-3}$)
ϱ_P	particle density ($kg\,m^{-3}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)

algorithms so that they fit to the user's case. In addition to this, all calculation routines are completely visible for the user.

Many researchers have already investigated the image analysis for multiphase flows and thus, many different algorithms are available ranging from manual to semi-automatic analysis procedures [20,21]. Fully automatic routines are rare and not always as precise as manual evaluation [22,23]. However, some standard image editing steps, like background subtraction and edge detection, have been established in literature [24–27]. For a detailed investigation of rising bubbles with at least 50 images per rise, the available algorithms are often not very practicable. Additionally, most researchers are only interested in the bubble size [11,28–30], which is calculated based on equivalent diameters due to the projection of a 3D object in a 2D plane, or the ascent rate [31–33], which is calculated measuring the time the bubble needs to travel a certain distance. An investigation of morphological parameters is often missing. Furthermore, only a few detailed time-resolved and simultaneous investigations of rising bubbles with respect to diameter, ascent rate and morphological parameters have been carried out. In this study, an improved automatic image analysis routine for time-resolved investigation of rising single bubbles in high-speed image sequences is developed using the open source software KNIME. A novel rotating Feret diameter for the calculation of an equivalent diameter is compared to the common calculation technique based on the major/minor axes.

2. System details

2.1. KNIME analytics platform

The developed image analysis routine was implemented in an open source KNIME analytics platform. KNIME is a graphical program for analysing data [34]. The workflow in KNIME is based on "nodes", which have analysing routines from different libraries implemented. In case of the Image Processing Extension these are BioFormats, SCIFIO, ImageJ, ImageJ2, OMERA and SciJava. Due to its highly modular basis, it was possible to implement an automatic analysing routine for measurements of Feret diameter, major/minor axes, and elongation as well as tracking of centroids positions. The data could be easily exported to Excel for further data treatment.

2.2. Analysing routine

The implemented analysing routine is shown in Fig. 1. The whole procedure can be split into ten elementary steps:

1. Import of the image sequence,
2. Projection of the maximum intensity,
3. Application of a quantile filter,
4. Background subtraction,
5. Determination of bubbles in the images,
6. Removal of images with bubbles touching the image border,
7. Extraction of bubbles as bitmask from the images,
8. Determination of Feret diameter as bubble diameter by rotation of the bitmasks,
9. Identification of further bubble characteristics, such as elongation and centroid position,
10. Export to Excel.

The import of the images into the workflow is carried out with the Image Reader node (1.). The image format can vary from .jpg, .png, .tiff

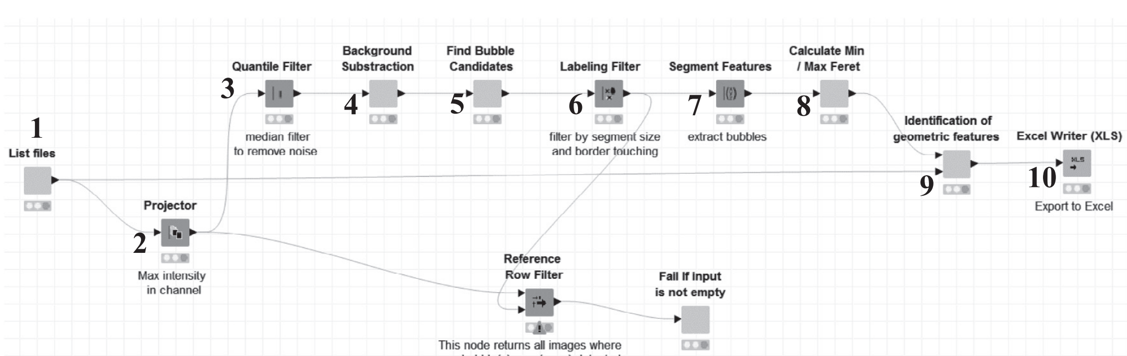

Fig. 1. Implemented analysing routine in KNIME (summarized flow sheet for a better overview).