Characterisation of hanging and detaching droplets using optical measurement setups

S Hummel, M Haub, M Bogner and H Sandmaier
University of Stuttgart / Chair Microsystems, Pfaffenwaldring 4F, 70569 Stuttgart, Germany
sebastian.hummel@mst.uni-stuttgart.de

Abstract. This paper presents two measurement setups to analyse hanging and falling droplets from different nozzles. The focus of these setups is on reducing costs and complexity of such systems compared to systems mentioned in literature which consists of an expensive high speed camera with according lens. Therefore the first setup uses an industrial camera and a corresponding lens having a resolution of up to 800 x 600 pixels and enabling the capturing of movies with more than 1000 frames per second (by using a reduced resolution). Additionally a weighing scale is implemented. The second setup represents a real low-cost approach, which nevertheless offers about 120 frames per second and a resolution of 640 x 480 pixels by using two RaspberryPi microcontrollers and the according camera modules. The cameras are placed in an angle of 90°. The presented setups are compared to each other and the advantages and disadvantages of each system are figured out. Subsequently the results of an exemplary measurement of the droplet volume are presented showing the quality of both setups with a maximum deviation of the optical results of less than ± 6 % compared to the results of the weighing scale.

1. Introduction
Size and shape of hanging and falling droplets are an old research area that mankind has been wondering about for a long time. Today droplets are widely used to measure small amounts of liquids for specific applications, for example in scientific laboratories for the preparation of different substances or in the clinical dosage of medication in infusions. Due to the importance of droplets their (exact) geometrical parameters are investigated for over 150 years beginning with comparatively easy approaches to estimate the maximum droplet size under quasi-static conditions by Tate [1], Rayleigh [2] and Harkins & Brown [3]. Other approaches, for example presented by Chesters [4], Eggers & Dupont [5] and Clanet & Lasheras [6], are based on differential equations which makes them on the one hand much more accurate and on the other hand much more complex than those presented in [1], [2] and [3]. Therefore Hummel et al. [7] presented a simple analytical approach with comparatively easy formulas and high accuracy to estimate the volume of falling droplets detaching from cylindrical capillaries.

To verify the presented approaches they have to be compared to real droplets detaching from an orifice. Investigations of real droplets, detaching from an orifice, are for example presented by Peregrine et al. [8] (cited by [5], for example), who uses a high speed camera setup with an exposure time of 15 µs to obtain clear photographs of a detaching droplet. A similar setup is presented by Shi et al. [9]. Just like Peregrine et al. they are using a flash illumination of the droplet from behind the droplet reaching exposure times of about 5 µs for their images. To obtain the named exposure time
complex setups are required including expensive high speed camera modules with corresponding lenses and a clocked flash illumination. However, if the requirements regarding the exposure time are lower than the values mentioned in this section, other approaches can be pursued. Therefore two approaches, which also reach high accuracy compared to cameras used in consumer electronics but which leads to a noticeably reduction of costs and complexity, will be presented within this paper.

2. Theory

2.1. Background
Both setups are based on the measurement setup described in [7] which consists of a camera and a corresponding lens on the one side of the investigated object and the illumination combined with a diffusor on the other side. This setup leads to an illumination of the object from behind. All the named optical components are aligned on one optical axis. To obtain satisfactory results out of this principle it is of significant importance to adjust the distances between the different optical components along the optical axis corresponding to the specifications of the used components.

2.2. Image Processing
To gain statistical relevance while analysing the volume of detaching droplets it is essential to have a look on more than one single droplet. To evaluate a larger amount of droplets it is necessary to create an evaluation algorithm which analyses the taken movies of the droplets and evaluates the desired geometrical parameters. The most important steps of this algorithm are presented in figure 1.

The output of the cameras used in the setups presented below is a movie file. In a first step this movie has to be separated into single grayscale images (figure 1 (a)) which can be evaluated. To create the required inverted binary images (figure 1 (b)) the grayscale images have to be converted. In this conversion it is necessary to choose a threshold, below that a pixel of the grayscale image is converted into black and above that it is converted into white. Afterwards the black and white pixels are switched to obtain the inverted binary image presented in figure 1 (b). Furthermore the bright center of the droplet (compare figure 1 (a)) due to the small deflection of the light in the center of the droplet, has to be colored as the rest of the droplet to avoid errors in the following contour detection. This contour detection leads to a white image with black pixels only where the contour is located (figure 1 (c)). Using an axis in y-direction through the centroid of the droplet as symmetry axis the volume of the droplet can be calculated by rotating the whole contour 180° around this axis using the equation

\[ V = \pi \int_{a}^{b} (f(y))^2 \, dy \] (1)

with the integration limits a and b being the minimum and maximum value of the contour in the direction of the y-axis.
This image processing is performed using the free library OpenCV, which is developed to enable the evaluation and modification of images and which is available for many common programming languages like C++ or Python.

3. Measurement setup

3.1. Setup 1 [10]: Industrial Camera

The first setup is developed having one optical axis which contains camera, lens, object, diffusor and illumination. For the image generation the camera UI-3130CP-C-HQ Rev.2 (IDS) connected to the lens HF16HA-1B (Fujifilm) with a focal length of 16 mm is used. Camera and lens are shown in the left part of figure 2. The object is illuminated by a LED with a radiation angle of 45° and the power of 1150 mW. This setup allows to record the droplet formation and detachment with a resolution of 800 x 600 pixels and 575 frames per second. The framerate can be enlarged to over 1000 frames per second by reducing the resolution or the observed area of interest.

![Figure 2. Cameras used for the presented setups: Industrial camera for Setup 1 on the left and the RaspberryPi camera module used in Setup 2 on the right.](image)

In addition to the optical measurement of the droplet the setup is equipped with the weighing scale Nimbus NBL254i (ADAM), which has a resolution of 0.0001 g and a standard deviation of 0.0002 g, to measure the average weight of droplets falling in a defined period of time.

To control and evaluate the measurement the camera as well as the weighing scale is connected to a personal computer. Based on the operating system Windows and the Qt framework a measurement and evaluation software is written in the programming language C++ supported by the OpenCV library. Within this software a graphical user interface is implemented.

![Figure 3. CAD-sketch (a) and photo (b) of Setup 1 with an industrial camera and corresponding lens [10].](image)

All components of the setup are assembled on a framework of aluminum profiles. The investigated object is a droplet dosing device which is assembled into a bottle. This bottle is aligned by being
matched to the notch of a 3D-printed attachment which is movable in vertical direction. A CAD-sketch and a photo of the setup are shown in figure 3.

3.2. Setup 2 [11]: Parallelized RaspberryPi Microcontroller
The second setup is designed with two optical axes. These two axes are disposed in an angle of 90° and the investigated object is the intersection of both axes. Both optical axes are equipped with a RaspberryPi microcontroller and the according camera module, which is shown on the right side of figure 2. This allows to record the droplet formation and detachment with about 120 frames per second and a resolution of 640 x 480 pixels. On both axes the same LED's as used in Setup 1 are installed. Due to the arrangement of the optical axis droplets can be evaluated by two sides. This enables a 3-dimensional alignment of the investigated droplets which increases the accuracy of the whole setup.

Both RaspberryPi microcontrollers are connected to each other via an ad-hoc-network. One of them is used as master controlling and evaluating the measurement process. The other one works as slave. Therefore a software with a graphical user interface is written in the programming language Python also supported by OpenCV. As operating system Linux is used.

![Figure 4: CAD-sketch (a) and photo (b) of Setup 2 with two RaspberryPi microcontrollers and the according cameras [11].](image)

4. Comparison of the setups

4.1. Advantages and disadvantages
Although both setups are based on the measurement setup described in [7], they have been developed with different goals and each of the setups has its particularities, advantages and disadvantages.

Setup 1 provides a comparatively high framerate combined with an easy and accurate alignment of the investigated capillary. A wide range of bottles can be used due to the wide range of possible settings. Except of the operating system the whole software is available as freeware. The developed measurement software allows the consideration of so called satellite drops, which arises in the droplet detachment process and enables the evaluation of a measurement with 15 s recording time in less than one minute. In addition to the optical measurement, Setup 1 is equipped with a high performance weighing scale allowing the verification of the optical results due to the different measuring principles. The setup demands a calibration of the optical system directly before each measurement which allows
the fast use of a wide range of different bottle sizes. Unfortunately this calibration is also time consuming and requires the setting of important parameters like the aperture and the focus of the camera system. Another important parameter to be set by the user is the threshold, which is needed to transform the grayscale image into a binary image (compare figure 1). Due to the wide range of setting options, which leads to the high flexibility of the setup, a reduction of the reproducibility of the optical measurement has to be accepted.

Due to the two optical axes Setup 2 allows an exact vertical alignment of the capillary. Unfortunately this leads to a much more complex alignment process than required in Setup 1. On the other hand the realignment of the whole system is required only if the investigated bottle size is changed. Compared to Setup 1, Setup 2 provides a minor flexibility due to a minor number of setting options and a reduced accuracy due to the rate of 120 frames per second, which is still high compared to cameras used in consumer electronics. By virtue of the exact alignment, the minor setting options and the fixed framerate, Setup 2 has a higher reproducibility than the above described Setup 1.

Comparing the hardware of both setups shows in both cases a significant reduction of the costs incurred for the setups compared to a standard high speed camera used in [8] and [9]. The costs for Setup 1 amount to about 1500 €. By using the RaspberryPi microcontroller combined with the according camera modules and the associated freeware costs can be further reduced in Setup 2 to about 300 €. Due to the lower calculation performance of a RaspberryPi microcontroller compared to a desktop computer, it has to be mentioned that the computing performance of Setup 2 is reduced in comparison to Setup 1 and leads to an evaluation time of about four minutes for a measurement duration of 15 s (which is still acceptable).

4.2. Results

To compare the results of the setups a measurement of droplet volumes has been performed [10, 11]. Therefore the droplet dosing device POMPL 0.6 S2, which is shown in figure 5, is assembled into a corresponding bottle with a nominal volume of 50 ml. Dosing devices like this are often used for the dosage of liquid medicine in the self-medication of patients. The bottle contains 30 ml of deionized and degassed water for each measurement. The duration of one measurement is 15 s which leads to about 20 investigated droplets. To obtain statistical relevance the measurement is repeated three times.

The measurement of Setup 1 results in an average droplet volume of 63.76 mm³ with a standard deviation of 1.55 mm³ for the optical investigation and 66.47 mm³ with a standard deviation of 0.46 mm³ for the measurement of the weighing scale. Setup 2 leads to average droplet volumes of 69.99 mm³ for the first optical axis and 67.27 mm³ for the second optical axis. The according standard deviations are 1.73 mm³ respectively 1.45 mm³. By checking these results the differences between the single values have to be mentioned. Due to the small standard deviation the result of the weighing scale measurement of Setup 1 will be used as reference. The deviations between the optical measured values are mainly based on the inaccuracies in the process of alignment of the capillaries. Compared to the measurement of the weighing scale these deviations does not exceed ± 6 %, but show clearly the challenge of calibration and alignment by using optical measurement methods. Nevertheless ± 6 % is a good result compared to the deviation of ± 10 % permitted by the European Pharmacopoeia [12] for droplets of liquid medicine. This shows the quality of the hardware and software of both measurement setups.
5. Summary and Conclusions
In this paper two measurement setups to evaluate the droplet formation and detachment at an orifice are presented. The focus of these setups is on reducing the costs and complexity of systems which usually uses expensive high speed cameras with according lenses.

Setup 1 is composed of an industrial camera with a corresponding lens and a high precise weighing scale with a resolution of 0.0001 g. The resolution of the camera is 800 x 600 pixels while reaching 575 frames per second. This framerate could be enlarged to over 1000 frames per second by reducing the resolution of the image. Setup 2 is made up of two RaspberryPi microcontrollers and the according camera modules which are arranged in an angle of 90°. The setup provides about 120 frames per second by reaching a resolution of 640 x 480 pixels which is lower than the value reached using Setup 1. In contrast to Setup 1, Setup 2 supplies a higher reproducibility due to a reduced number of setting options because setting options, which generates the flexibility of Setup 1, at the same time, constitute sources of errors.

Within this paper the two setups are compared to each other theoretically and in the context of a measurement of the volume of detaching droplets. Comparing the results of this measurement the result of the weighing scale of Setup 1 shows the lowest standard deviation and is used as reference for the optically measured values. The results of the optical measurements in both setups show a deviation of less than ± 6 % which confirms the quality of both setups.

Acknowledgments
Great thanks to Ferdinand Hummel and Philip Wolf who designed and assembled the described measurement setups during their studies at the Chair Microsystems. Some of the figures are based on their work, too.

References
[1] Tate T 1864 The London, Edingburgh, and Dublin Philosophical Magazine and Journal of Science 27 176-180
[2] Rayleigh L 1899 The London, Edingburgh, and Dublin Philosophical Magazine and Journal of Science 48 321-337
[3] Harkins W D and Brown F 1919 Journal of the American Chemical Society 41 499-524
[4] Chesters A K 1977 Journal of Fluid Mechanics 81 609-624
[5] Eggers J and Dupont T F 1994 Journal of Fluid Mechanics 262 205-221
[6] Clanet C and Lasheras J C 1999 Journal of Fluid Mechanics 383 307-326
[7] Hummel S, Bogner M, Haub M and Sandmaier H 2017 MDPI Proceedings 1(4) 284
[8] Peregrine D, Shoker G and Symon A 1990 Journal of Fluid Mechanics 212 25-39
[9] Shi X, Brenner M P and Nagel S R 1994 Science 265 219-222
[10] Hummel F 2018 Optimierung eines optischen Messstades zur Tropfenanalyse (Student Work, University of Stuttgart / Chair Microsystems)
[11] Wolf P 2018 Optimierung eines Messstades zur optischen Tropfenanalyse unter Verwendung zweier Raspberry Pis und synchronisierter Kameras (Student Work, University of Stuttgart / Chair Microsystems)
[12] Ph. Eur., Europaeisches Arzneibuch (8. Ausgabe, Grundwerk 2014) (Stuttgart: Deutscher Apotheker Verlag)