Uncertainty of the shadow method for the analysis of evaporating droplets

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Abstract. The shadow method of image analysis is the most commonly used experimental technique for investigation of evaporating droplet dynamics and wettability. So, the shadow method uncertainty and limit of its applicability for analysis of evaporating droplets are actual issues. In this paper, we experimentally study the applicability limit of the shadow image analysis and contributions of errors, connected with non-telecentricity of the optical system, as well as diffraction and numerical errors, at various stages of droplet evaporation.

1. Introduction
The continuously increasing interest to processes of droplet evaporation and wettability is connected with many important applications such as spray cooling [1,2], inkjet 3D printing [3,4], DNA chip manufacturing [5], and nanoparticle structuring [6]. Many recent studies [7-12] are directly related to fast development of droplet-based microfluidics and nanofluidics.

Nowadays, the shadow method of image analysis is the most commonly accepted optical technique for studying droplet evaporation and wettability [13-17]. However, non-telecentricity of the optical system, lens diffraction, edge diffraction (Fig. 1) and errors of numerical method of droplet outline detection limit the accuracy of the shadow image analysis.

The substrate surface texture may appreciably affect the droplet symmetry. There are several image processing techniques of outline detection applicable to both symmetric and non-axisymmetric drops. In the polynomial fitting approach presented in [18], a necessary number of knots from the drop contour are extracted using various methods of edge detection (Sobel operator [19], Canny method [20], mask segmentation [21]) and segmentation by intensity thresholding) and fitted by a polynomial. This method is simple in implementation but requires high computational cost so as accuracy depends highly on the polynomial degree and on the number of knots. Sub-pixel polynomial fitting method (SPPF), presented in [22] is more accurate and suitable for automated computer implementation. In this method droplet contour is found in sub-pixel resolution using saddle point of the sigmoid of pixel intensity; contact points are found by extrapolating and intersecting droplet contours with their reflection. In this paper modified DropSnake metod [23] was used to extract droplet outline and measure the contact angle in a fully automotive mode.

Marangoni convection on the gas/liquid interface of a droplet [24,25] makes estimation of errors more complicated. Moreover, dependence of light reflections on the droplet shape should be taken into account. In this paper we experimentally study the limit of applicability for shadow image analysis and contributions of errors, connected with non-telecentricity of the optical system, diffraction and numerical errors, at various stages of thin droplet evaporation.
2. Methodology
To verify the shadow method, the mass of evaporating sessile droplets was measured using shadow image analysis and precise weighing on analytical balance.

Recent experimental studies [26,27] have shown that axisymmetric model of sessile droplets is very simplified in many cases (especially in the last stages of sessile droplet evaporation). So, to improve accuracy of droplet volume measurement we reconstructed 3D shape of the droplet using a side and a top camera. Imaging plane of the side camera was placed perpendicular to the substrate. The top camera's imaging plane was placed parallel to the substrate. The images synchronized with CPU time were processed in MATLAB to detect 2D contours of evaporating droplet using DropSnake method (side view) and Snake method (top view). It allowed reconstructing the droplet shape and obtaining all necessary geometrical parameters.

Measurement frequency of the analytical balance was 5 fps. Values on the display were registered using the third camera NIKON D200 at a frequency of 4 fps. Digits on the display images were recognized automatically using MATLAB Image Processing Toolbox. A NIKON D200 camera was synchronized with CPU time within 0.1 s.

2.1. Acquiring Images
Images of droplets acquired from side and top views were synchronized in time to within 0.05 s using MATLAB Image Acquisition Toolbox. We used the VideoDevice System object for single-frame image acquisition with timestamp. System objects were designed specifically for analyzing dynamic systems with inputs that change over time. The images from two cameras were taken alternately. This approach allowed improving synchronization precision and avoiding losses. Before acquisition a Region of Interest (ROI) was selected for each frame to optimize computing costs. Afterwards, frames were analyzed using MATLAB Image Processing Toolbox.

Before the start of the measurements, intrinsics, extrinsics, and lens distortion parameters of the cameras were taken into account using Camera Calibrator app (MATLAB Computer Vision Toolbox). These parameters were used to remove lens distortion effects from the images. Pixel distances for side and top images were converted to metric length units (mm) using the measured diameter of the substrate.

2.2. 3D Reconstruction of the Droplet Shape

Figure 2. Slice-method. The plane of the approximating circle is parallel to the main optical axis of the side camera.
To determine the three-dimensional shape of evaporating thin droplet we use combination of contours from side and top views simultaneously. The droplet volume is constructed from approximating circles which plane is parallel to the main optical axis of the side camera. The principle of this method (slice-method [28]) is presented in Figure 2.

DropSnake method is used to detect 2D contours from shadow droplet profile (Fig. 3). The initialization of the active contour in the first frame is performed manually. The initialization of subsequent frames is based on the solution of the preceding frame because droplet volume decreases continuously during evaporation.

![Figure 3. DropSnake method.](image)

![Figure 4. Snake method.](image)

Snake method allows detecting the droplet outline from top view image (Fig. 4). The initialization of the first frame is performed by intensity threshold using Otsu’s method. The initialization of the subsequent frames is performed similarly.

### 3. Experimental setup

![Figure 5. Experimental setup.](image)
The scheme of the experimental setup is presented in Fig. 5. Mass of the sessile ethanol droplet evaporating on the copper substrate was measured using analytical balance A&D BM-252 to within 0.01 mg. Ethanol droplet evaporated at the temperature of 23 ºC. Weighing chamber and fine range ring were used to avoid weighing errors caused by convection and to achieve the diffusion-dominated transport conditions. The shadow optical system consisted of a diffuse light source (LED coupled with white diffusing glass) and a side camera Imaging Source DMK23G031 (with resolution of 2592×1944, dynamic range of 12 bit, frame rate of 5 fps) with a macro lens (Nikon 200 mm f/4D ED-IF AF Micro-Nikkor). The top camera Imaging Source DMK23G021 (1280×960, 12 bit, frame rate of 5 fps) was coupled with a NAVITAR HR objective (F2.8/50 mm). Fiber Optic Ring Light Guide with illuminator Edmund Optics MI-150 were used to acquire images of droplet from top view.

4. Result and discussion
In this experiment we investigated uncertainty of the shadow image analysis for determining the three-dimensional shape of evaporating thin droplet with contact angles not exceeding 20°. The results are shown in Figures 6 and 7.

![Figure 6](image1.png)
**Figure 6.** Dependence of the droplet mass on evaporation time.

![Figure 7](image2.png)
**Figure 7.** Relative error of droplet mass determination using shadow method vs. contact angle.

From Fig. 7 it is seen that the relative error in the droplet mass determination using shadow method does not exceed 5 % at contact angles higher than ~10°, when the main contribution to the error is induced by the numerical method. The relative error of mass determination increases sharply at angles lower than ~10°. Non-telecentricity of the optical system results in overestimation of droplet profile at final stages of evaporation (Fig.8).

![Figure 8](image3.png)
**Figure 8.** Non-telecentricity of the optical system leads to overestimation of the droplet contour on the last stages of evaporation.
However, it is necessary to take into account the error of weight measurements associated with the average recoil impulse of evaporating ethanol molecules to correctly estimate errors. This error reaches 0.1 mg at the last stages of evaporation.

The resolution of shadow images in experiment is 4 microns / pixel. The error due to lens diffraction in macro mode (F/D≈5.3) is ~3 microns. Edge diffraction on the liquid-gas interface for diffuse light can be neglected (~0.5 micron).

Using data from Fig. 7 one can calculate that the error in determining the droplet height at the contact angle of 6 degrees is about 50 microns that significantly exceeds the diffraction and numerical errors, as well as the pixel resolution of the camera. This means the main contribution to the error of the shadow image analysis method is induced by the non-telecentricity of the optical system. The use of telecentric lenses in combination with monochromatic telecentric light [29] reduces the error in determining the droplet height to a diffraction error (Fig.9).

**Figure 9.** Image-forming of evaporating droplet in a telecentric optical system.

**Conclusions**
The paper presents an experimental study of the applicability limit of the shadow image analysis and contributions of errors, connected with non-telecentricity of the optical system, diffraction and numerical errors, at various stages of thin droplet evaporation. It has been found that the shadow method in non-telecentric optical systems can only be used for droplets with contact angles greater than ~10°. We suppose that the use of telecentric optical system can significantly increase resolution of shadow image analysis for determining the three-dimensional shape of evaporating thin droplets.

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