Microflows with Moving Boundaries: Experiment and Simulation

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ABSTRACT

Surface forces and capillary effects can play a dominant role in fluidic microsystems. Therefore it is crucial for simulations to use accurate numerical approaches [1]. Furthermore experimental data gained from such surface dominated systems can be used to test different numerical methods for dealing with moving boundary problems. This paper presents the real-time visualization of collisions of water microdroplets on an inclined steal plate. This model experiment shows the features of wetting and dynamic contact angles. The frame of 8 images recorded with a multi channel high-speed camera coupled to an optical microscope is treated by specially developed digital image processing tools to correct geometrical distortions and to extract object features. The above mentioned experiment is compared to the simulation results obtained with a commercial code [2] which uses the VOF algorithm [3].

Keywords: Microfluidic systems, free surface flow, high-speed visualization, CFD code evaluation

1 INTRODUCTION

Moving boundary problems are often referred to as free surface problems since the unknown boundary has to be determined as part of the solution procedure. Problems of this class are important in many technological applications such as melting, solidification, wetting and many other areas in engineering and science. For the case of microfluidic systems such moving boundaries are encountered e.g. in microdosing systems, when sprays of microdrops are produced or when fluid quantities enter and exit microchannels.

An additional difficulty is present if droplet wall interactions are present. Beside the surface tension on the liquid/gas interface the solid/liquid interface has to be modeled. If the droplet is spreading after its impingement on a solid surface a moving contact line has to be considered. If a no-slip condition is applied and a continuum approach is used it can be shown that this description leads to a force singularity at the contact line [4]. To circumvent this inconsistency several slip prescriptions have been proposed [5]. Unfortunately this results in an unphysical recirculation in the slip zone which has to be considered as an artifact of the proposed models. On the other hand molecular dynamics simulations [6] show that the no-slip condition on the solid boundary is valid everywhere, except for distances on the order of a couple of molecular diameters in the vicinity of the contact line. For this reason approaches have been proposed which simulate this problem without the introduction of local slip or other ad hoc mechanisms [7]. The direct calculation of moving contact lines and dynamic contact angles is described in this communication as a result of the special free surface reconstruction using the VOF algorithm [3].

The accurate modeling of such phenomena is very important in many technical applications, like coating technology, combustion engines or spray cooling devices. Therefore any proposed numerical approach has to match experimental data obtained with model systems which are completely dominated by the above mentioned surface effects. Free surface microfluidic systems are the ideal test cases since the importance of body forces such as gravitational effects are significantly reduced. Here first results of real-time visualizations of splashes of water microdrops on inclined steal surfaces are reported and compared to results obtained with the above mentioned commercial code [2, 7].

2 VISUALIZATION

The visualization of moving fluid surfaces usually means the need to cope with high speed processes. If we deal with experiments which do not show transient phenomena stroboscopic techniques can be used. This was used in the first report about a visual study of drop impact which was published by Worthington [8] in the 19th century. Though for systematic experimental investigations we had to wait for the advent of high-speed camera systems. Engel [9] was one of the first authors publishing high-speed camera recordings of water drops colliding with various solid surfaces. But until today only visualizations of splashing drops down to the mm regime have been presented [10], [11]. Moreover optical magnification in order to access the μm scale increases the challenge for the speed of the recording systems used. Our experimental setup which fulfills these needs is described in the next section.

2.1 Experimental Setup

The tests presented in this paper have been performed with real high speed cinematography using a ultra high speed micro motion analyzer developed by us [12]. As main part of this test rig the commercial ultra high speed camera Imacon 468 from DRS Hadland Ltd. has been optically coupled with a standard microscope Zeiss Axioplan via a fibre optic plate. Inside the camera, relay optics channel the light onto a special beam splitter consisting of an eight-sided mirror pyramid from where it passes to eight intensified CCD units. The CCD sensors which are arranged in a circle around the beamsplitter are amplified by micro channel plate (MCP) units mounted in front of the CCD camera sensor. They act as high speed shutters to determine the ultra short exposure time of 10ns of the camera. A self designed light source provides a pulse of 50Mcd generated in a Xenon flash lamp. Figure 1 and 2 show the working principle of the ultra high speed micro motion analyzer and an image of the setup respectively.

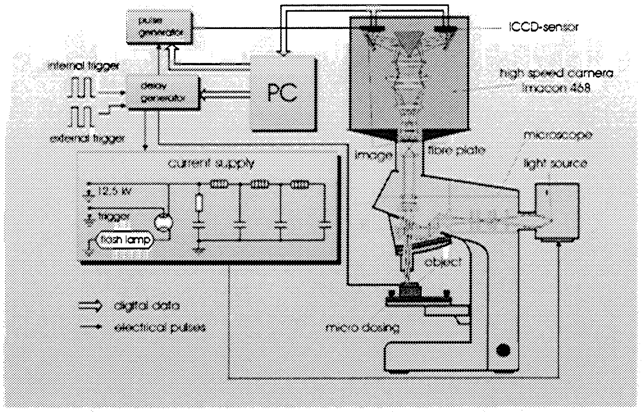

Figure 1: Working principle of the experimental setup.

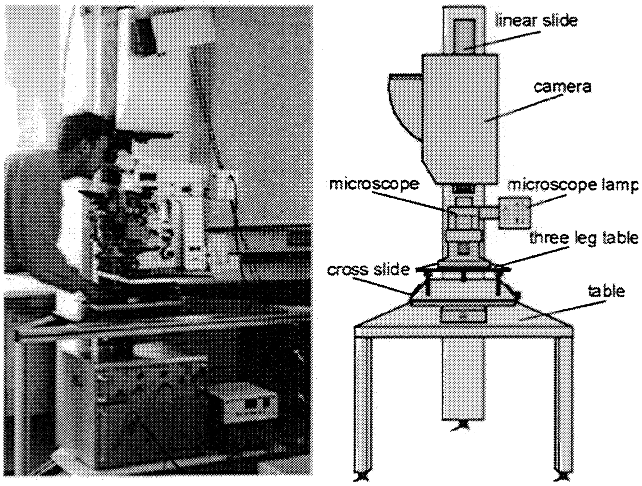

Figure 2: Ultra high speed micro motion analyzer.

2.2 Image Processing

The 8 independent real-time images produced by the Imacon 468 camera show geometrical image distortions which have not been sufficiently corrected by the camera's acquisition software for our purpose of measuring the contours of the inspected free surfaces flows. In order to reduce the geometrical distortions down to subpixel deviations a three point correction with an optimized affine transformation matrix is used. This image correction is part of a self developed digital image processing system which allows object detection based on template matching and dynamical thresholding combined with parameter based region selections. User interactions such as the drawing of boundary lines are also included in our software application which is implemented using HALCON library routines and Visual C++. Figure 3 shows a screen shot of our digital image processing system evaluating one of the frames of a microdrop splash on an inclined surface which is presented below (figure 6).

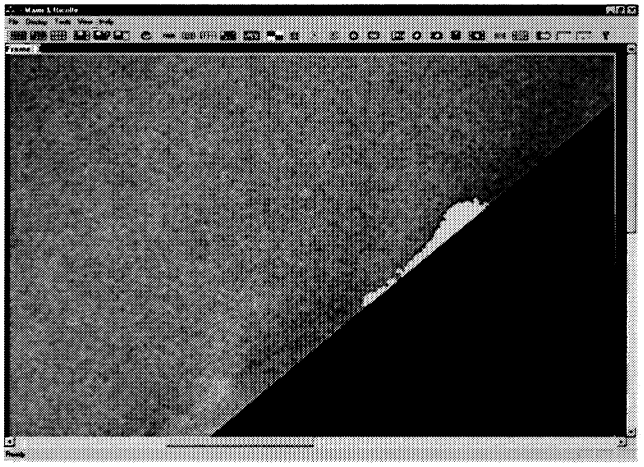

Figure 3: Digital image processing system.

3 MICROSPLASHES EXPERIMENT

The experimental results show the splash of a microdrop of distilled water with a diameter of 13μm at room temperature on an inclined steal plate. This experiment features the dynamics of the droplet impingement together with advancing and receding contact angles. The size of the image corresponds to a field of view of 220μm to 147μm.

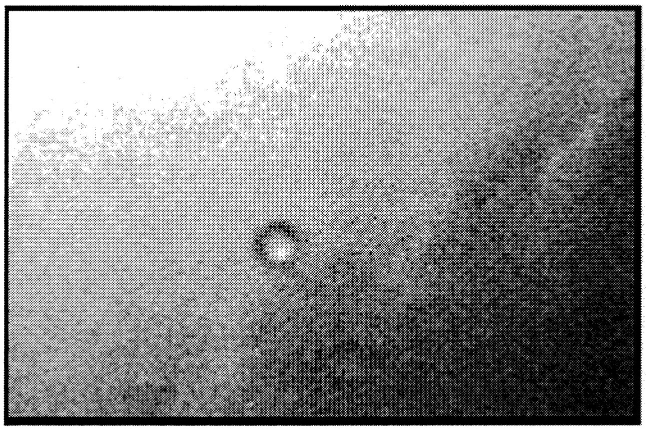

Figure 4: Water droplet of 13 μm before splash (0μs).

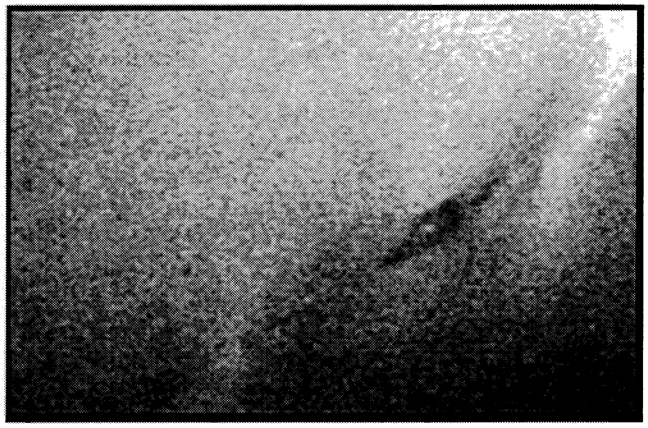

Figure 5: Impact of microdrop (4μs).

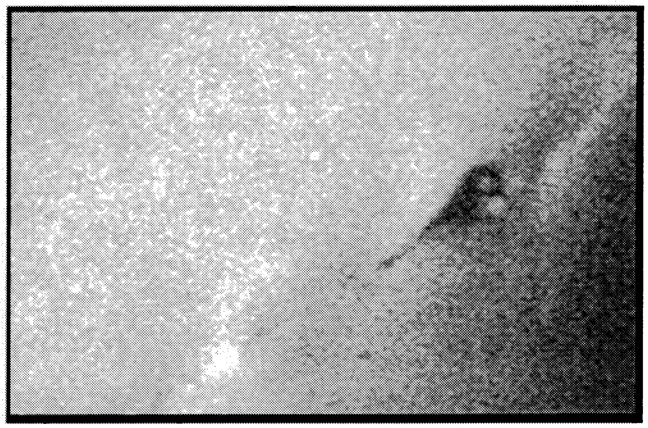

Figure 6: Microdrop moving on the steal plate (8μs).

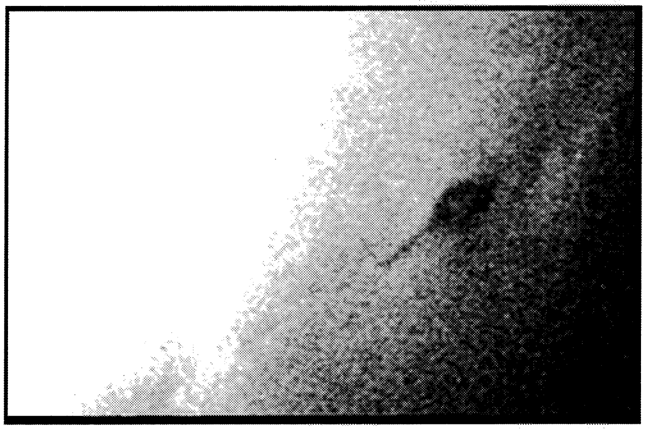

Figure 7: Retracting microdrop (12μs).

The microdrop in the above image sequence is produced by a thermal printhead which has never been filled with ink in order to avoid any pollution of the dispensed water which might affect the surface tension. The velocity of the water microdrop was determined from the first pictures of the image sequence not presented here to be 7m/s. The exposure time of the images is 500ns.

4 MICRODROP SPLASHES - SIMULATION

As a comparison to the experiment shown in the previous section a full 3D simulation of the microdrop splash is calculated using Flow-3D [2]. Water at room temperature and the measured contact angle of water on the steal plate are introduced as material parameters into the simulation.

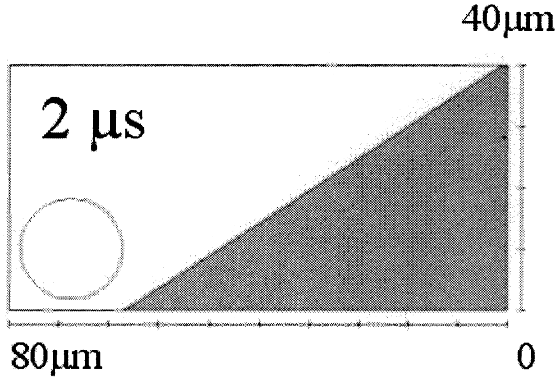

Figure 8: Simulation of micro splash after 2μs.

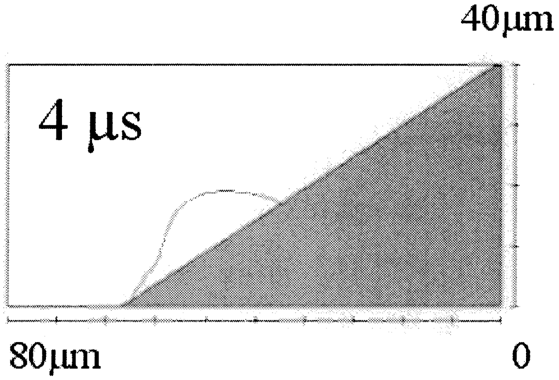

Figure 9: Simulation of micro splash after 4μs.

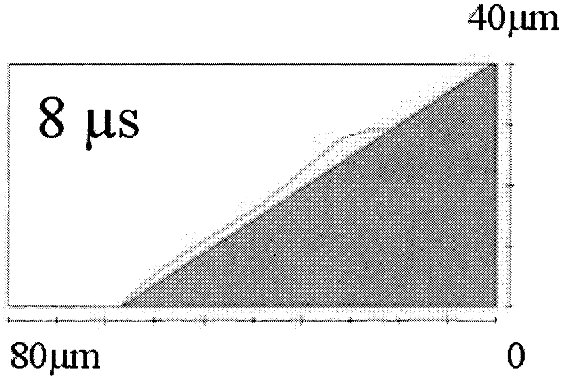

Figure 10: Simulation of micro splash after 8μs.

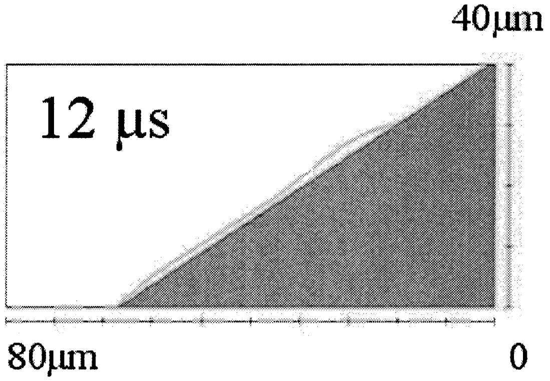

Figure 11: Simulation of micro splash after 12μs.

5 CONCLUSION

We have presented first model experiments featuring fluidic microsystems with free surfaces. Using such model systems the effects of liquid/gas and liquid/solid interfaces can be studied. Our aim is to provide image data which serves as an experimental reference for numerical algorithms dealing with moving boundary problems.

In this communication only a qualitative comparison between the experiment and the simulation is made. As the main deviation of the simulation results using commercial code it can be noticed that the liquid once advanced on the surface is not retracting and does not accumulate in a compact form as can be seen in the experiment. This also holds for long simulation times which have not been presented in the last section.

A more detailed and also quantitative numerical-experimental comparison is in progress. Our experimental setup is about to be improved. The goal is to have improved, corrected image data, both the original images and the extracted contours of the free surfaces, to be accessible for CFD code evaluation and development on the web page (www.mrm.e-technik.uni-ulm.de) of our department.

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