Results in Optics 8 (2022) 100266

Contents lists available at ScienceDirect

Results in Optics

journal homepage: www.sciencedirect.com/journal/results-in-optics

A case study of optical methods for measuring thickness of liquid sheets

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ARTICLE INFO

Keywords:
Optical physics
Optics

ABSTRACT

We demonstrate that the usual optical methods can be applied in a simple way to quickly estimate thickness of liquid sheets on sub-millimetre scales. It is shown that an approximate linear relation can be obtained between gap thickness and several of the usual RBG and HSV variables (red and green pixel values in the RBG case and saturation in the HSV case). The method we use is viable as long as the sheet does not become too thin and is much simpler than other dye-based optical methods for determining the thickness.

1. Introduction

A topic of central importance in industry and fluid dynamics is the possibility of experimentally measuring thicknesses of liquid films on the microscale. This is generally a very difficult task and countless techniques have been proposed over the past hundred years based on various physical principles and depending on the flow (Vernay, 2015; Tibiriçá et al., 2010). One key application is to estimate the thickness of the splash crown which is ejected during the impact of a solid sphere on a free liquid surface or the impact of a liquid droplet on a solid surface. Direct measurements of the thickness of this liquid sheet during ejection are almost impossible, although if small holes open in the walls, it is possible to use the Taylor-Culick relation for propagation of hole edges to estimate the sheet thickness in terms of the surface tension of the liquid and the speed at which the holes open (Lhuissier and Villarmaux, 2009; Marston et al., 2016). The method used in (Marston et al., 2016) can only measure the thickness on top of the lamella, where it becomes very thin.

Existing experimental methods are sophisticated and can be broadly divided into four classes: acoustic, nucleonic, electrical (including conductance-based and capacitance-based methods) and optical (including interface detection, light attenuation, and laser displacement) (Tibiriçá et al., 2010). Optical methods are relatively straightforward and simple compared to the other possibilities, so unsurprisingly there have been many proposals for optics-based techniques to measure film thicknesses. These include techniques based on optical interferometry, fluorescence methods, diffusing light photography, and light absorption methods (Ohyama et al., 1988; Makarytchev et al., 2001; Berhanu and Falcon, 2013; Lilleleht and Hanratty, 1961; Kim and Kim, 2005). In this article, a simple optical method is proposed for estimating thickness of a silicone oil film below 1mm using coloured dye. In Section 2, the experimental set-up is described and in Section 3, the results are analysed to show that a relation can be obtained between liquid thickness and certain of the RBG and HSV variables. Our method is quite close to that of (Kim and Kim, 2005), but note that their method uses photochromic dyes which are activated via irradiation with a laser, whereas the experiment proposed here does not require lasers or fluorescent dyes. However, the method described here is only useful for estimating the thickness and cannot be used to perform accurate measurements.

The use of optical methods to determine liquid film thickness have been studied very intensively, including very recent studies which use completely non-invasive optical methods to make high-precision thickness measurements of transparent liquid sheets ranging from thicknesses of micrometres up to millimetres (Razzaghi et al., 2020). Phase shifting interferometry and equal-path interferometry have also been adapted for thickness measurements (Deck, 2014; Deck et al., 2014). The only novelty of this article is essentially that we show that these methods which have been used many times with varying degrees of sophistication to measure thicknesses of liquid sheets can also be adapted to a simple case study which allows a demonstration of the usual principles using only a camera. In Section 2, we describe our experimental set-up. This is followed by a discussion of the results obtained in Section 3. We then conclude and discuss further work in Section 4.

2. Experimental set-up

Two transparent glass slides with height 7.7cm, width 5.1cm and thickness 0.1cm are fixed so that they stand upright and meet at the bottom at an angle as shown in Fig. 1. The gap thickness between the top of the slides is measured to be 1mm and the thickness decreases linearly as one goes to the bottom of the slides, where the gap thickness is measured to be 0.1mm. The images captured in Figs. 1 and 3 were taken using a Photron FASTCAM SA-X2 high-speed video camera in snapshot mode, but a more basic camera can be used. Backlighting is provided by a single light source of luminance $178,256\,\mathrm{cd\,m^2}$ and uniformity 99.44%.

https://doi.org/10.1016/j.rio.2022.100266
Received 4 April 2022; Received in revised form 20 June 2022; Accepted 6 July 2022
Available online 9 July 2022

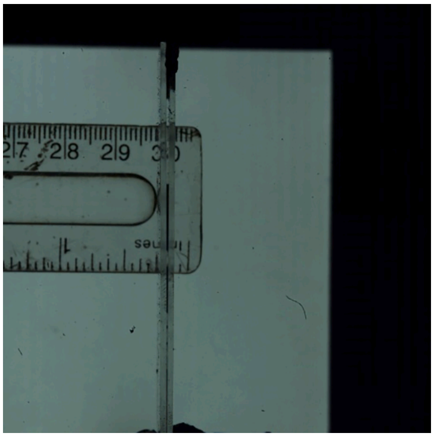

Fig. 1. Pair of glass slides fixed upright at an angle.

The experimental set-up with the light and camera is shown in Fig. 2. The total gap thickness is then filled with 2 cSt silicone oil which has been dyed using Solvent Blue 14 (shown in Fig. 3). The spacing between the top of the slides is fixed and the slides are glued in place, as otherwise surface tension from the liquid in the gap will pull the plates together. The slides are sealed at the bottom and sides to prevent liquid from draining out as the gap thickness is filled. The deviation in the path of a light ray at different heights due to the angle of contact at the bottom is assumed to be negligible as the plates are extremely close to being parallel.

The concentration of the dye is chosen such that a clear difference in brightness can be observed as one moves from the bottom to the top of the slides. Note that the same concentration used in the calibration with the slides must then always be used in experiments if one wishes to estimate the thickness of a liquid sheet during an impact. Here for calibration purposes 0.038 g of dye powder is dissolved in 30 ml of silicone oil. The same amount of dye must be scaled up when dying an entire liquid bath which is then used to study liquid sheets ejected during sphere impacts or similar phenomena. The measurements were performed at ambient temperature and ambient pressure.

3. Discussion

Fig. 3 shows visible variation in the ‘brightness’ of the blue colouring as one moves from the bottom to the top of the cell. To begin, a strip is chosen from the bottom to the top of the plates for analysis (shown as inset in Fig. 4). There is some ‘noise’ in this spectrum, but this is avoided by choosing a line from left to right during image processing which avoids noise fragments. The aim is to show that certain properties can be related approximately linearly to the gap thickness, at least for sub-millimetre thicknesses within certain ranges. As expected, the blue pixel value cannot be used to obtain any useful information, as seen in Fig. 4 (left). In Fig. 4 (middle) and Fig. 4 (right), the red and green pixel values, respectively, are plotted against gap thickness. It can be seen that the relation for the red pixel value is close to linear between 0.3 and 0.8 mm and that the relation for the green pixel value is close to linear between 0.2 and 0.7 mm.

Fig. 2. Experimental set-up showing camera and pair of glass slides.

Fig. 3. Cell filled with dyed oil.

The RGB values are then converted to HSV values, where H is the hue, S is the saturation, and V is the value (roughly corresponding to a brightness scalar). In Fig. 5 (left), the value is plotted against gap thickness and it is again found that no useful information can be obtained in this case. In Fig. 5 (middle) and Fig. 5 (right), the hue and saturation, respectively, are plotted against gap thickness. It can be seen that the hue is not useful for obtaining a linear relation, or at least not in any ranges which are not already available using RGB values. However, for the saturation the relation is approximately linear over a wider range than that accessible for RGB values (between 0.3 and 0.95 mm). Since the concentration which we have used is known, one can scale the amount of dye used and apply it to a larger liquid body. The liquid sheets during impact can then be studied using high-speed photography. The calibration could also be repeated with different concentrations if necessary, which may also depend on the liquid.

4. Conclusions

To conclude, we have demonstrated that a dye method can be used to estimate thickness of liquid sheets within a reasonable range below a thickness of 1 mm and above a thickness of 0.2 mm. Although this does not cover many much smaller thicknesses which would be of interest when studying very thin liquid films, it allows one to study a range of thicknesses which can regularly occur during study of droplet impact and sphere impact problems (Marston et al., 2016). Estimating the thickness of these sheets is generally a very hard problem owing to the transient nature of the phenomenon and the difficulty involved in obtaining useable images from high-speed photography. Many methods do exist for performing accurate measurements but these are sophisticated and would not necessarily be available or even viable in all laboratories.

A weakness of the method described here is that it will probably fail to give a good estimate once the liquid sheet becomes very thin. As mentioned in the Introduction, this will be problematic when considering the very top of the lamella during a sphere impact, although it could potentially be used elsewhere on the lamella closer to the sphere. However, the method does seem to give a close to linear relationship between thickness and optical properties of a dyed silicone oil sheet as long as one stays within a reasonable range which one would expect to see in an impact or liquid jet ejection event. One future possibility for obtaining accurate measurements would be to use a confocal chromatic

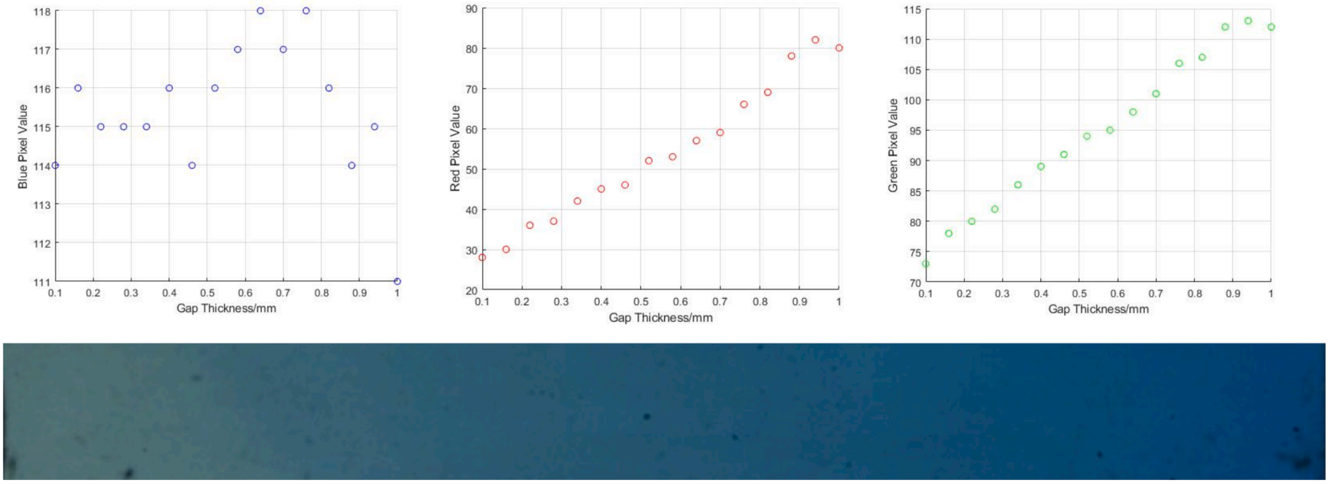

Fig. 4. Gap thickness against blue pixel value (left), red pixel value (middle) and green pixel value (right).

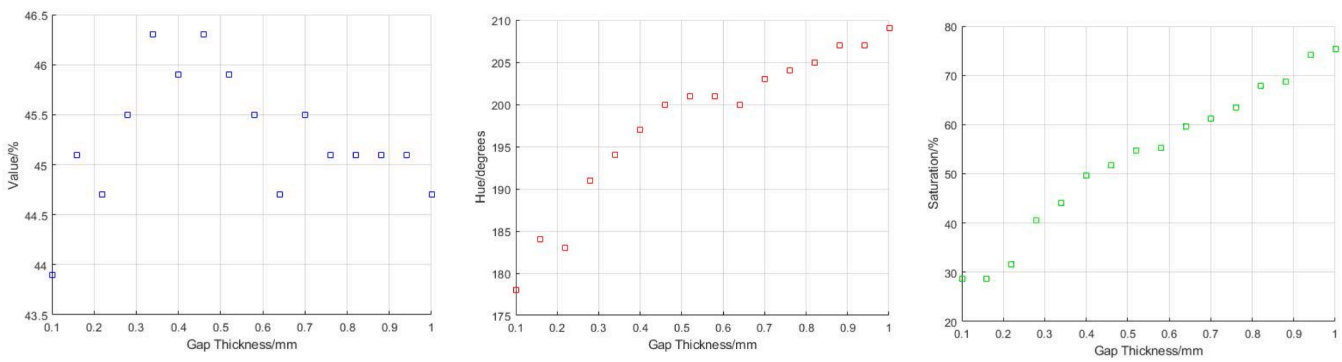

Fig. 5. Gap thickness against value (left), hue (middle) and saturation (right).

sensor which points at the ejecting sensor. Such a device has been used previously to measure the film flow over a transparent surface (Burzynski and Bansmer, 2018). Given the cost and difficulty of more sophisticated methods, a simple optical method such as the one which we have explained here is of interest and may also prove useful in experiments. It might also be possible to refine the experiment and use it to produce more accurate measurements, in which case it could then be a competitor to other more sophisticated dye-based methods in the literature (Kim and Kim, 2005).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research has been financially supported by EPSRC Grant No. EP/N016602/1.

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