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► **To cite this version:**

J. Blaisot. Analysis of backlight images for spray measurement: how to accurately identify the liquid-gas interface in images. ICLASS 2018, Jul 2018, Chicago, United States. hal-02371921

HAL Id: hal-02371921

<https://hal.science/hal-02371921v1>

Submitted on 20 Nov 2019

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Analysis of backlight images for spray measurement: how to accurately identify the liquid-gas interface in images

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Abstract

We present in this paper the key points for using backlight images in spray measurement. The main features of a spray accessible from backlight images are the interface contours of the liquid elements. It is commonly considered that using this kind of images is straightforward, notably because these images are directly understandable by a human being. However, making image-based measurement needs a rigorous approach. The first point is the setting up of the optical system. Although no special expertise is required to make images of sprays, a particular attention must be put on the imaging system and light source arrangements when relevant measurement are expected. Also, different steps must be considered to correctly estimate liquid-gas interface localization on backlight images. First, attention must be put on the pretreatment of the images to correct light source defects such as spatial or temporal in-homogeneity. For the segmentation step that follows, local intensity variations in the images are analyzed to determine the localization of the liquid-gas interface contour in the images. It is shown that modeling the image of liquid elements is mandatory to correctly estimate these features. Based on the results of this modeling, several local parameters are proposed. It is shown how the local shape of the interface acts on the variation of these parameters. Finally, partial overlapping of images of liquid elements is considered and solutions for discriminating potential overlapping liquid elements in an image are proposed.

Introduction

Image analysis is among the most promising measurement methods for achieving improved characterization of sprays. Images result from the projection of 3D objects onto 2D image plane. As such, information relative to the third direction are lost or at least hidden. However, by appropriately analyzing images, some of these information can be recovered.

Spray measurements are no longer confined to the spray drop size distribution but comprise now the objective to quantify more deeply the liquid-gas interface properties. First attempts were oriented to the determination of shape parameters but the objective is now to quantify the surface area of the interface of every liquid elements in a spray, whatever their shape. To do that, an accurate determination of the interface location is needed. Backlight imaging techniques are particularly well suited for this purpose. Indeed, at least the shape of the liquid elements directly appears on the images. However, all necessary precautions are not always taken in experiments, and this is mainly due to preconceived ideas about images.

First, an imaging set-up may seem easier to arrange as it does not require a rigorous optical alignment to obtain the image. The problem arise when starting to use this image to make the measurement. Second, the image is directly interpretable by a human being. This easy perception gives rise to the feeling that image will be measurable as soon as image can be "understood" to the naked eye. This is far from it as a measure needs signal processing operations that may fail in case of bad images.

One important drawback in using images comes from the depth-of-field (DOF) of the optical system. A spray is three dimensional by nature so images of liquid elements are focused or not, depending of the location of these elements relative to the focus plane. In addition, when spray drop size distribution is considered, the drops must be counted in a given control volume, sorting the droplets by accounting their distance from the focus plane. This must be done through the use of objective criteria determined from signal modeling, as done for all other measurement techniques.

A review of the key points of the optical set-up is first addressed. Important steps in image analysis operations are then presented. Finally, some issues relative to the determination of the liquid-gas interface location in images are tackled.

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Experimental setting up key points

A backlight imaging system is composed of two main elements, i.e. the light source and the imaging arrangement.

The spectral (white or monochromatic) and temporal (continuous or pulsed) properties of the light source obviously conditions the quality of images notably by influencing spectral aberrations and movement blur and as such are always considered. The divergence of the light source also has a significant impact on image usability but is less often considered. Diffuse light sources are used in DBI (Diffuse Backlight Imaging) techniques whereas collimated light sources are employed in Schlieren imaging configuration when sensitivity to refractive index variation is wanted (density gradient induced by phase change, temperature or pressure gradient for example). Even if diffuse light sources are more easy to set up as they do not require a great attention in position and alignment, collimated or quasi-collimated light sources should be favored as they contribute to a better (sharper) silhouetting of the liquid elements in the spray. In fact, a true collimated light is not required but the more collimated the source, the more forward light scattering near the optical axis direction is promoted. This results in images that put emphasis on object contour and thus on liquid-gas interface. It can be noted that a collimated light source helps in obtaining images with a better contrast and also tends to improve DOF.

The optical characteristics of the imaging arrangement that must be first considered are the magnification and the aperture. These parameters determine the field of view (FOV) and the DOF. The combination of FOV and DOF defines the measurement volume of the imaging system, i.e. the portion of the 3D-space where liquid objects are detectable and are measurable. The magnification obviously determines the FOV in combination with the size of the sensor of the camera, but also plays a role on the DOF. Indeed, the higher the magnification the shorter the FOV and the DOF. Given measurement constraints, the choice for the magnification must be given by the finest details of interest to be measured in spray images. This is an important point because even if 2D images are considered, when very fine details are wanted (as for drop sizing in Diesel spray for example [1]) the setting up of the imaging system can turn it in a rather local measurement method with FOV below millimeter sizes.

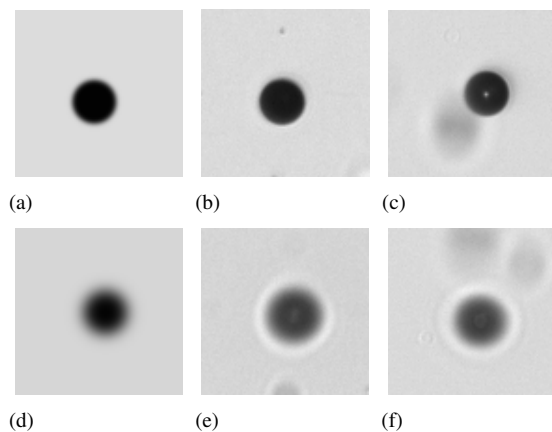


Figure 1. Images from the model (a,d), from circular discs (b,e) and water droplets (c,f).

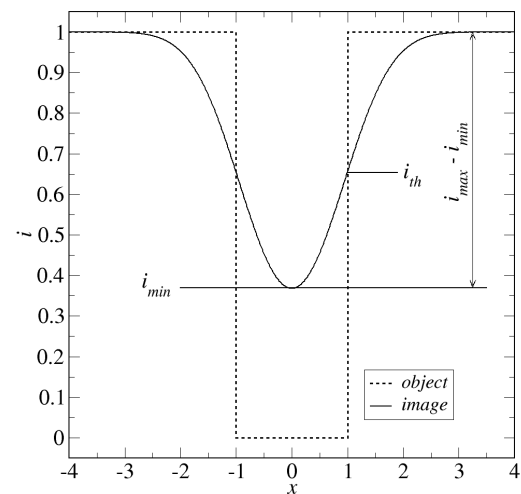


Figure 2. Example of a modeled image profile for circular object of radius $a = 1$.

The aperture directly determine the DOF but also the background level in backlight images. The setting of this parameter is a trade-off between DOF and background image illumination, i.e. low aperture is needed for large DOF but high aperture is necessary to reach adequate signal-to-noise ratio. The DOF can be characterized through the determination of the Point Spread Function (PSF) of the imaging system which corresponds to the optical image of an infinitely small object point. For the PSF to be characterized by the imaging system, small pixel size is needed. Digital image capturing systems can be classified in two categories: Pixel Limited (PL) systems and Optics Limited (OL) systems. An optimum is usually wanted by adjusting the PSF width to the pixel size (PL systems) but in this case the PSF characteristics are not accessible from the images. For an OL system, the minimum spot of an imaged point covers at least several pixels. This allows the PSF width to be measured on the image. It can be noted that miniaturization of image devices bring chips with increasingly small pixel size, offering better conditions to setup an OL system.

The PSF is a function of the three coordinates in space. It is often considered not to vary in the image plane but this only applies locally as geometric or chromatic aberrations induce changes in the PSF shape as soon as off-axis regions are considered. The way the PSF width varies with out-of-focus (OoF), i.e. in the direction perpendicular to the image plane, depends on optical parameters such as magnification and aperture but also on the divergence and the spectral properties of the light source. The PSF can be approximated by a Gaussian:

$$PSF(r) = s_0 e^{-r^2} \quad (1)$$

where $r = \sqrt{\frac{2(x^2 + y^2)}{\chi^2}}$ is the non-dimensional position in the image plane, (x, y) are the coordinates in the image plane, χ is the PSF half-width and s_0 is a normalization coefficient. Non-dimensional quantities for the position in the image plane will be used in the following.

The PSF width is minimal in the focus plane and increases with OoF due to the increase of aberration. It can be noted that PSF width is usually minimum near the FOV center, i.e. near the optical axis where aberrations are minimum. The DOF is determined from the variation of the PSF width with z , the distance to the focus plane along the optical axis. As this distance increases, the diffraction limit worsens and finest details are no longer resolved. For PL systems, the maximum limit is expressed by the pixel size, i.e. DOF is the distance at which PSF width equals the pixel size. For OL systems we are considering here, the maximum limit is related to the finest scale that must be resolved, for example the minimum droplet diameter when drop sizing is concerned. In this case, the limit is directly related to the visibility of this finest scale. Practically, the DOF is determined from the calibration of the imaging system by the distance at which the smallest droplet is measurable (see for example Fdida and Blaisot [2]).

The information of interest in spray images is the location of the liquid-gas interface. We just consider here the location of this interface in the 2D plan resulting from the projection of the 3D space to the 2D image. It means that we will deal with dimensional measurement on the image through the analysis of the object contours. Measurements in the third direction (perpendicular to the image plane) considered here only correspond to the determination of the DOF.

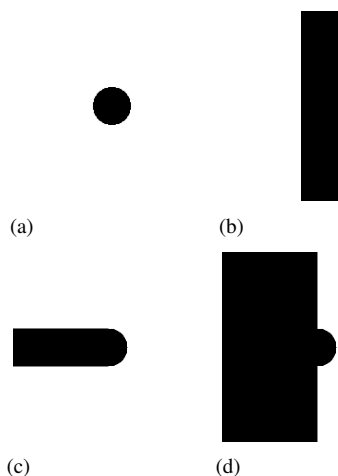


Figure 3. The different interface shapes considered: (a) *drop* shape, (b) *jet* shape, (c) *ligament* shape and (d) *bumped edge* shape. The *straight edge* shape not presented on this figure is just the shape (d) without bump.

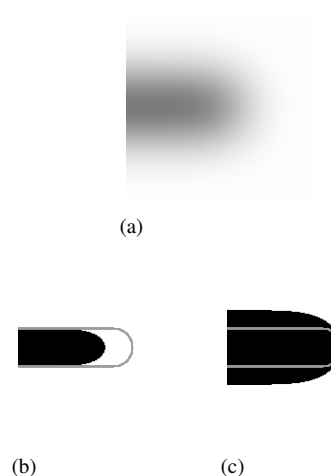


Figure 4. Example of a *ligament* shape blurred image (a) on which *jet* shape criterion (b) or *ligament* shape criterion (c) is applied. The original contour is indicated in light grey.

Liquid elements in a spray are intrinsically refractive objects. However, due to surface-tension effects, liquid-gas interface is never totally flat and has got a 3D shape implying a curvature directly appearing in the image but also occurring perpendicularly to the image plane. It can be noted that local interface curvature is all the more high that the size of the local detail in the contour is small. Thus, the light coming from a quasi-collimated light source and refracted near the object contour is strongly deviated due to the local orientation of the interface. This prevents any light coming from this region to reach the image sensor. Hence, near the interface, liquid objects just appear opaque. For example, images of liquid droplets or opaque discs are very similar as can be seen in figure 1

and droplets can be modeled as opaque or slightly transmitting discs. As only contour localization is concerned, focus is essentially put on the edge of the modeled image profile as shown below.

Image analysis and liquid-gas interface identification

The non-uniform background illumination is often an issue when dealing with backlight images of sprays. A normalization procedure can help in attenuating these background defects. Moreover, the fraction of transmitted light is assessed through a normalization operation expressed by equation 2:

$$I = \frac{I_{raw} - I_{noise}}{I_{back} - I_{noise}} \alpha \quad (2)$$

where I_{raw} is the raw spray image, I_{back} is the background image (obtained without any object in the view field) and I_{noise} is the black noise image (obtained with the camera objective closed). The coefficient α is determined by estimating the light pulse energy in order to compensate illumination shot-to-shot variations (see [1] for details). Only imaging devices with linear response must be considered (no gamma-correction applied) and subtraction of black noise is necessary for I to correspond to the fraction of transmitted light.

An important point in signal analysis is signal to noise ratio (SNR). Backlight imaging has the big advantage of producing high level signals as the background signal is (or should be) near to the maximum level. A well adjusted systems thus exploit the entire dynamics of the sensor. The local background level I_{back} must then remain over a minimum level to guarantee a minimum signal-to-noise ratio. A minimum value for the background can be given by half the maximum level of the image level dynamics (i.e grey level 127 for 8-bit images). However, the effective signal dynamic (compared to background) reduces as object size diminishes. In backlight configuration this is called the contrast of an image that constitute one of the main parameter in spray image analysis (see below).

Criterion for interface identification

The criterion for the choice of the contour pixels at liquid elements boundary is usually based on intensity level or on intensity gradient [5, 2, 6]. Object contour are characterized by a local variation of intensity from bright levels in the background to dark levels in the object. It is straightforward that the region of interest is near from local mid level, corresponding also to the local maximum intensity gradient. As noise can remain in the image and can induce low accuracy in gradient estimation, the preferred approach is based on an intensity level criterion, i.e. image segmentation by application of a threshold. The choice for the threshold is crucial to locate accurately the interface. A good way to obtain this threshold is to consider a criterion obtained from the modeling image formation.

A PSF approach based on Fourier optics formalism has been developed by the author [1, 2]. It expresses the illumination distribution in the image plane by the convolution product of the irradiance distribution in the object plane and the PSF of the imaging system. The modeled image profile well describes the real image profile near the object contour.

An example of image profile for a circular object (i.e. a droplet) is shown in figure 2. The object function for this object is also displayed. These profiles are normalized, meaning that the maximum level is $i_{max} = 1.0$ and the minimum level $0.0 \leq i_{min} < 1.0$ where $i_{min} \rightarrow 0.0$ for large objects. The amplitude of the intensity profile of an image $i_{max} - i_{min}$ is expressed as usual by the local image contrast $C = (i_{max} - i_{min}) / (i_{max} + i_{min})$ which is a non dimensional quantity. The contrast tends towards 1.0 for big or well focused objects and tends to 0.0 for very small or out-of-focus ones.

The criterion for the localization of the interface is deduced by regarding the image profile at the object edge. The intersection between the rectangular object function and the image profile gives the exact position of the object edge on the image profile, yielding to the threshold level i_{th} . To make this threshold more universal it is expressed as a relative quantity $l^* = \frac{i_{th} - i_{min}}{i_{max} - i_{min}}$. This relative threshold allows determining interface localization whatever the range of grey level values in experimental images and constitutes the criterion for interface localization.

Influence of shapes on interface localization criterion

Drops, jets, ligaments and liquid sheets are commonly encountered in sprays and present different types of contour shapes. The images of these objects are obviously not similar, even in the vicinity of the object edges. To take into account the variety of object shapes, several shape models have been considered, corresponding to drop, jet, ligament and straight or bumped edges (see figure 3). The *drop* shape obviously account for drop images. The *jet* shape gives indication for very elongated liquid objects like jet or ligament as long as object end is not considered. For this latter case, the *ligament* shape is used. Finally, the *straight edge* and *bumped edge* shapes

are considered when the liquid object is so broad that only one side influence the image profile. The straight edge represent the edge of a liquid sheet whereas the bumped edge represent a locally deformed edge of a liquid sheet. All the shapes considered are only concave shapes and are characterized by a radius of curvature a , except for the straight edge. Note that for the *jet* shape the jet edges appears straight on the image. Indeed, the curvature is present in a plane perpendicular to the local axis of the jet so in a plane perpendicular to the image plane in this case.

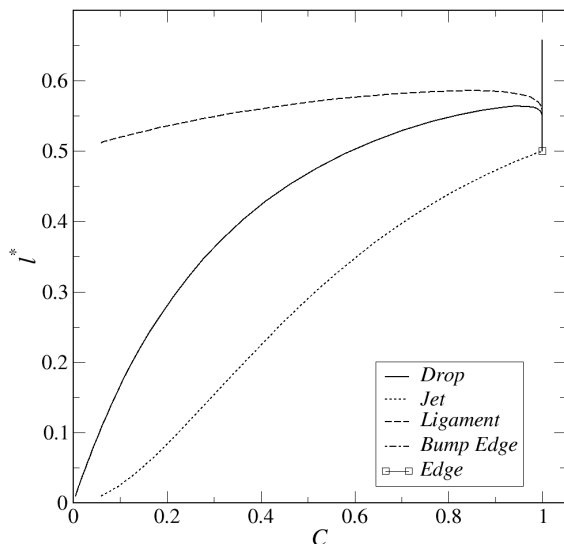


Figure 5. Sizing criterion for the relative threshold level l^* as a function of contrast for different types of interface.

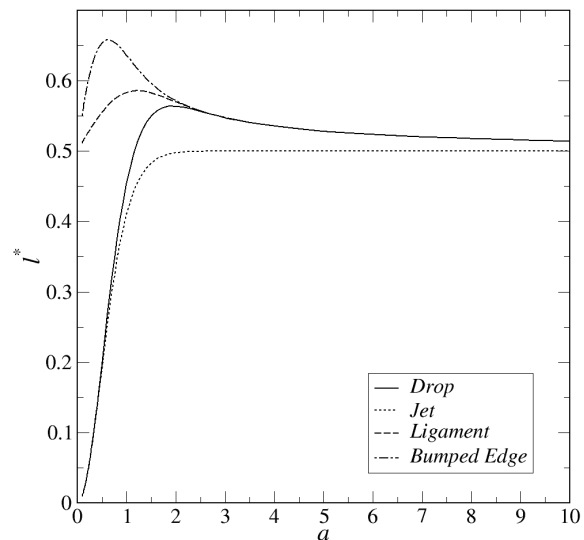


Figure 6. Sizing criterion for the relative threshold level l^* as a function of local normalized radius of curvature for different types of interface.

The criterion l^* for interface localization is derived from image profiles of the different shape models. Image profiles oriented horizontally (for the shape orientation shown in figure 3) and at middle object vertical position are computed. The variation of l^* versus local image contrast is shown in figure 5. As intuitively guessed, mid relative level is reached for the criterion as soon as objects are sufficiently focused, i.e. when contrast is high enough. However, for unfocused objects, the criterion greatly depends on the shape, indicating that great discrepancies can occur if incorrect criterion is used for a given shape. For *drop* and *jet* shapes the relative level decreases to 0.0 as contrast does. Indeed, image of such objects getting more and more blurred also lose contrast as objects being more and more defocused. This results in more and more flat image profile that require the relative level to be placed near the minimum level, i.e. $l^* \rightarrow 0$. As noise in experimental images prevents from using too flat image profiles, an usual minimum limit is given by only considering images with contrast higher than 0.1. For the *straight edge* and *bumped edge* shapes the contrast remains equal to one as for such shapes the object always covers a large portion of the image leading to high contrast (i.e. low i_{min} value) even when edge is blurred by defocusing. Thus the criterion remains $l^* = 0.5$ for the *straight edge* and varies between 0.5 and 0.65 for the *bumped edge* only due to the change of the local curvature at the bump (see below). The *ligament* shape criterion shows a different behavior from the *jet* shape as it remains between 0.5 and 0.6. It means that whereas the interface is located near relative mid level at ligament end, it reaches far lower level when leaving the ligament end. An illustration of this is given in figure 4 where the blurred image (fig. 4(a)) of the ligament in figure 3(c) is analysed either with the *jet* shape criterion (fig. 4(b)) or with the *ligament* shape ones (fig. 4(c)). The original contour is indicated in light grey on these images, showing that none of the criteria is correct over the entire contour. The *jet* shape criterion gives the correct estimation of the interface far from the ligament end whereas the *ligament* shape criterion is correct only at the ligament end. In fact, to recover the original shape of the interface, a variable criterion should be applied, taking into account the local radius of curvature of the interface. This last point constitute an issue for the experimental determination of the interface contour as the interface should be known to determine the good criterion to use for the localization of the interface. Nevertheless, even if the real localization of an interface is not obtained with a bad criterion, the general shape of the contour gives a good indication of the real shape. A two-step procedure can thus be employed, where the first step uses an a priori criterion to determine the shape and

the second step uses the good criterion corresponding to this shape.

The effect of the local radius of curvature of the interface on the localization criterion is reported in figure 6. The size parameter a (rendered dimensionless by multiplication with $\sqrt{2}/\chi$) corresponds to the radius of the *drop* or of the *jet* or *ligament* shapes. It corresponds also to the bump radius for the *bumped edge*. It is clear that when a approaches infinity, the criterion level reaches 0.5 whatever the shape model. This is also the case for the *straight edge* shape for which $a = \infty$. The criteria for *ligament* and *bumped edge* shapes, and also for *drop* with $a > 1.2$, remain greater than 0.5 and are even identical as soon as $a > 2$ with a reduced dependency on a . The criterion goes below 0.5 for the *drop* shape with small a (i.e. for circular object smaller than the PSF) because of the low contrast of these objects. The criterion for the *drop* and *jet* shapes are almost identical for $a < 1$, and as object radius increases, the two criteria increase separately to converge again for very large object.

These results show that except for very large objects, the criterion for interface localization in backlight images greatly depends on the local curvature of the image. Indeed, for large value of the radius a (relative to the PSF width χ), the criterion $l^* \simeq 0.5$, corresponding to what is intuitively expected. However, in the range of values $0 < a < 5$ the strong dependence of the localization criterion l^* on the local curvature of the interface indicates that a precise estimation of the interface position cannot be reached by generalizing such intuitive criterion. Thus, taking into account the local properties of the contour shape is mandatory for a good estimation of the interface of liquid elements in a spray images.

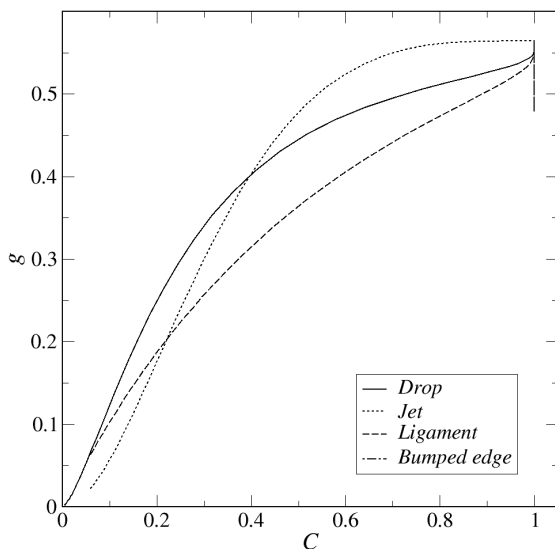


Figure 7. Intensity gradient at relative level l^* as a function of contrast for different types of interface.

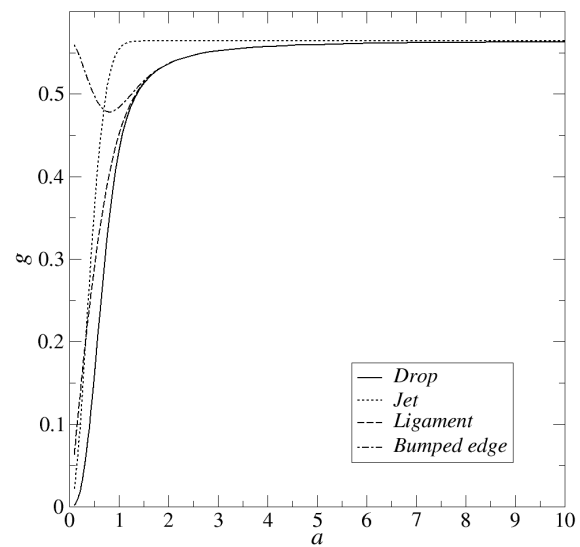


Figure 8. Intensity gradient at relative level l^* as a function of local normalized radius of curvature for different types of interface.

Image overlapping

Objects are identified in two-level images after the operation of segmentation. An object is the interior of a contour identified as the liquid-gas interface (see previous section). As backlight images are formed by the projection of silhouettes of 3D objects on a 2D plane, what is identified as an object in the image can indeed correspond to the silhouette of only one real object or to the superimposition of the silhouettes of several real objects that form a single contour. In this latter case, partial overlapping of image have to be identified to prevent several real objects to be treated as only one segmented object.

Partial overlapping identification

When real objects partially overlap, only a part of the contour is accessible for each object. To identify contours that correspond to partially overlapped objects, a local analyses of the contour must be done. The intensity gradient at contour points must be considered. Indeed, one obvious property of overlapped objects is that they are not located at the same out-of-focus position in the measurement volume, otherwise they would have coalesced in only one object. As shown by Fdida and Blaisot [2], the intensity gradient at contour points is a property sensitive to the

level of focusing and can be used in a criterion for unfocused level estimation. The variation of intensity in the contour region is directly related to the shape of the PSF that changes with OoF position and for an OL imaging arrangement, the PSF width can be estimated by measuring intensity gradients near the object contour.

The intensity gradient at relative level l^* corresponding to the interface (i.e. interface identification criterion) is plotted in figure 7 as a function of the local contrast for the different shapes considered, except the straight edge. For this later one, the intensity gradient at mid level is identical to $1/\sqrt{\pi}$, the maximum intensity gradient reached for all the other shapes. It must be recalled that this gradient is expressed in non-dimensional coordinates (i.e. $\sqrt{2}x/\chi$ if x is the dimensional variable). Thus, as expected, the effective gradient of a focused object will tend to infinity as soon as the PSF half-width χ tends to zero. The reason for the intensity gradient to tend to zero with contrast (as does the interface identification criterion) is here again directly related to the flattening of the intensity image profile for unfocused objects.

Results in figure 7 exhibits that the intensity gradient does not show a great dependence on the object shape in its variation over contrast values. This is particularly helpful here so that the gradient can be used as it is as a criterion for discriminating different contour parts located at different OoF positions. Moreover, the variation of the intensity gradient with the radius of curvature is also weakly depending on the shape as can be seen in figure 8, except for the edge shapes (straight or bumped). For these reasons, the intensity gradient can be used as a criterion for discriminating partially overlapped contours without considering the local curvature of the interface.

Partial overlapping treatment

An example of partial overlapping treatment is shown in figure 9. It clearly appears to the naked eyes that crossing liquid structures in the image of figure 9(a) are not in the same focus plane. Particular regions of interest are marked with a circle identified with a letter. Contours determined from liquid-gas interface identification procedure are shown in figure 9(b). At this first step, the contour is a continuous line describing the interface of every liquid object in the field of view and the contour parts belonging to the different objects are not separated. When local intensity gradient is considered, separation between the different contour parts is more clear as can be seen in figure 9(c). The horizontal color-bar in this figure stands for the range of colors corresponding to gradient from minimum to maximum value, from left to right.

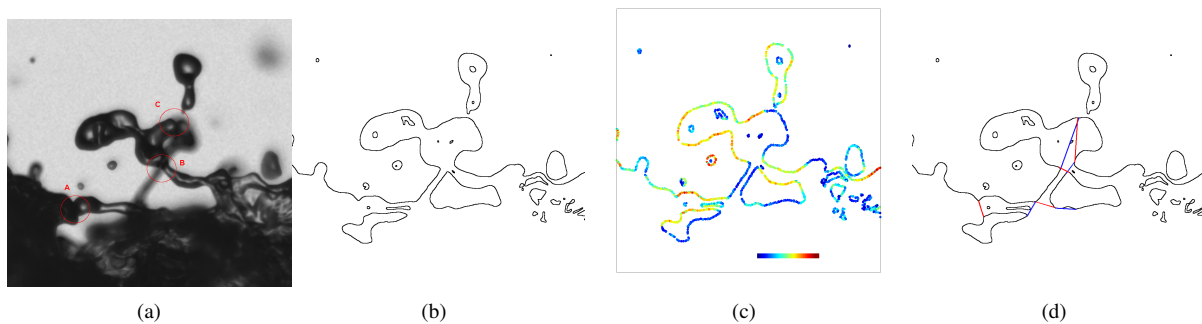


Figure 9. Treatment of overlapping: (a) example image showing local superimposition of liquid objects; (b) contours of the image in (a); (c) contour points colored by intensity gradient values and (d) contours continued by identification of overlapping.

The first point is to identify every potential overlap points in the contour by detecting steep gradient variations over the connected contour points. Then, pairs or potential overlap points must be connected together. This is down by taking into account the following constrains: 1) the new connection cannot go outside the former segmented object, i.e. the new contour section must cover regions over liquid parts (dark regions in the image) and not over gas (light regions); 2) the new connection must be as short as possible; 3) the end of the connection must present an angular region if no steep gradient variation occurs; 4) new connections segments cannot overlap.

Different kinds of overlapping appear on the image of figure 9(a), indicated by red circle labeled from 'A' to 'C'. In region 'A' a *straight edge* and a *ligament* overlap. The upper contour of this region clearly shows a change in gradient value (see corresponding part in figure 9(c)) but the gradient varies more continuously in the lower part of the overlapping. The end of the connection is the nearest point in the contour that is located at an angle in the contour.

In region 'B' high gradient sections are easily connected by identification of the nearest overlapping point with similar gradient values. The overlapping points with a lower gradient value in region 'B' have to be connected with

the point in region 'C' in a way that no overlap occurs between the new connections. All the new connection parts are indicated in figure 9(d). Obviously, using straight connections is not physically efficient in most of the case but more advanced treatments have to be considered to propose connections with more realistic shapes.

Summary and Conclusions

It has been shown that when dealing with liquid-gas interface identification, the local properties of the image profile in the vicinity of the object contour has to be determined. The criterion for the local relative threshold level for the interface positioning must take into account the local image contrast and the local curvature of the interface itself. The mid-level criterion that is intuitively guessed by simple considerations is actually reached for edges with a high contrast and a large radius of curvature. However, for many parts of the contour edge in a spray image, a sharper analysis must be done to correctly estimate the interface location. This imply several step in the procedure that has been presented in the first section of this paper.

The issue of partial overlapping of contour edges has also been considered in the second part of the paper. Local intensity gradient is considered to be a good criterion to detect potential overlap points in contours initially detected from interface detection addressed in the first section of the paper. It was shown that this gradient can be used as it is as a criterion for overlap detection. The principle of the treatment of potential overlap points thus detected is presented.

The future works will concern the full automation of the overlap detection and more realistic estimation of the contour hidden by overlap phenomenon.

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