A Simple Off-Line Automatic Image Analysis System with Application to Drop Sizing in Two-Phase Flows

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An automatic image analysis system has been developed, and used initially for obtaining size distributions of droplets in two-phase flows from multiple photographs with sub-microsecond exposure. It requires only a conventional, relatively cheap television camera and computing facilities likely to be available in any laboratory undertaking such work, avoiding the need for expensive purpose-built equipment. Image recognition and subsequent processing, e.g., rejection of unfocused images, are dealt with by software, based on detection at eight grey levels. The system and its calibration are described, and a typical analysis is presented and compared with a manual sizing.

NOTATION

A	image area
d	diameter of drop, calibration disc, or their images
h	halo width
I	image intensity; video voltage representing intensity
P	image perimeter
x	coordinate along TV scan line
y	coordinate normal to TV scan line

Subscripts

a	actual value
c	corrected measured value
m	measured value
1 to 4	intensities defined in text or Fig. 1
1A	intensity at grey level 7

1 INTRODUCTION

A typical example of the need for mechanical and chemical engineers to study liquid drop behaviour in two-phase flows is the adverse effect of coarse water drops on wet-steam turbine performance. These drops are formed by atomization of films and rivulets stripped from blade and casing surfaces and are of order 10 to 100 μm in diameter. Studies of their behaviour, e.g., (**1**), play an essential part in attempts to understand the causes of wetness losses, both mechanical and thermodynamic, and of erosion. In related laboratory work, the major measurement problem is in obtaining drop size distributions, for which several optical techniques appear to be applicable, including photography, low-angle light scattering, and laser diffraction.

Early work on this topic (**2**) successfully used high-speed photography, but manual analysis of the photographs is an exceptionally tedious operation, severely limiting the quantity of data which can be handled; assessing the degree of focus of a drop image is a very subjective procedure, so that consistent results cannot be obtained. The chief disadvantage of methods which involve recording the characteristics of scattered or transmitted light, followed by a mathematical transformation to relate this to the size distribution, is the time and effort required to develop the necessary expertise and perfect the instrumentation. Examples of such techniques are described in (**3–5**). While instruments based on light scattering principles are available commercially, it is often difficult to justify their cost, or to use them effectively where they require the two-phase flow to be sampled. More recently, laser Doppler anemometer systems have been used, e.g., (**6**), drop size being related to the ratio of the modulation to the mean signal, but the size range is limited by ambiguity in the results.

Photography remains a favoured method in view of its directness, simplicity, non-interference with the flow, and low cost. Applications exist (**7**) where high droplet concentrations preclude use of other optical methods, owing to multiple scattering. To ease the analysis problem it is now usual to consider automatic image analysers of the type available commercially (e.g., the Imanco 'Quantimet', now manufactured by Cambridge Instruments). Ramshaw (**8**) described a technique based on such an instrument as early as 1968. They consist basically of purpose-built detectors which scan the image, and hardwired logic elements which assign to each 'picture point' (on a grid covering the image) a 'grey level' (light intensity value); further modules analyse this digitized information to produce a limited number of attributes for each detected feature (area, perimeter, etc). More recent examples incorporate minicomputers to replace some of the hardwired logic. These instruments are most commonly found in laboratories concerned with metallographic or geological work, have a high capital cost (of the order of £50 000 at present) and often have peripheral equipment suited only to their prime task of analysing well-defined objects/images with sharp outlines.

As part of a study of drop coagulation in two-phase pipe flows, related to cross-over pipe flows in nuclear wet-steam turbines, the authors have investigated many image analysis systems and concluded that very few are capable of handling the type of photograph produced

Received 2 November 1979 and accepted for publication on 14 January 1980.
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0142/727X/80/0300–0047$02.00 © MEP Ltd 1980

from their rig, in which a high proportion of drop images are inevitably 'out of focus'. Only analysers with extensive software control through a peripheral computer **(9)** or with internal hardware modifications **(10)** were able to perform automatic rejection of the blurred images of drops outside a chosen depth of field. Reliance on remote installations for all processing needs was judged to be impracticable, especially for development work. Accordingly, an existing two-grey-level (i.e., black/white) system **(11)** has been developed, at low cost, into an eight-level system in which rejection of unwanted images is handled entirely by software, giving greater flexibility than hardwired proprietary equipment.

This paper reviews briefly the techniques used with existing image analysers, describes the hardware and software of the present system, and presents typical examples of its performance.

2 SOME EXISTING IMAGE ANALYSIS SYSTEMS

Jones **(10)** describes the principles of obtaining size spectra via 'Quantimet' image analysing computers, both his own installation, on which wiring modifications have been made, and the Sheffield University system which is interfaced to a desk-top computer. The basic 'Quantimet' is unable to carry out the required analysis unless the operator 'edits out' detected images considered to be out of focus, thereby retaining the subjectivity of a manual analysis.

A peripheral computer enables a focus criterion to be applied in the form of a stored calibration which relates the measured drop diameter and the width of the blurred region, known as the halo, to the drop's position relative to the plane of best focus. Figure 1, showing intensity (or greyness) variation across well-focused and poorly-focused drop images, indicates how such a criterion might be defined in terms of the intensity gradient at the edges of the image. In both refs **(9)** and **(10)**, the gradient is defined in terms of two intensity levels I_2 and I_3 intermediate between the background level I_4 and the peak level I_1. For each photographic negative being analysed, I_1 and I_4 may be measured, and I_2 and I_3 set as fixed proportions of $I_1 - I_4$, determined from a calibration. 'In-focus' images may then be defined by

$$h < h' \qquad (1)$$

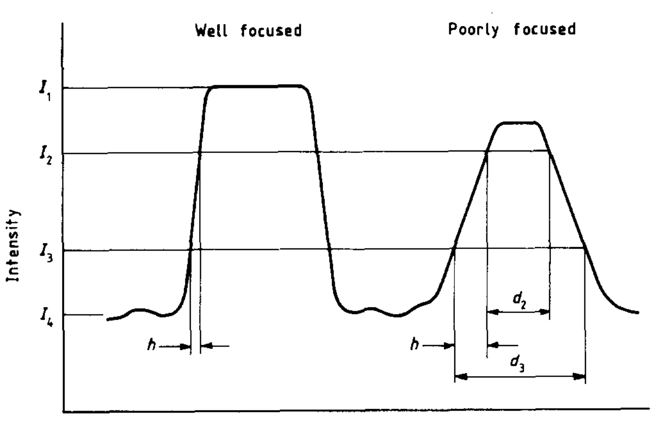

Fig. 1. Effect of degree of focus upon intensity variation across a drop image

where halo width h is given by

$$h = \tfrac{1}{2}(d_3 - d_2) \qquad (2)$$

and d_3 and d_2 are the measured diameters at levels I_3 and I_2 respectively. For a particular depth of field, chosen to give a reasonable number of 'in-focus' images on a typical photograph, h' may be found to be a function of the measured diameter d_m (which might, for example, be defined as $\frac{1}{2}(d_2 + d_3)$). A corrected diameter d_c might then be obtained by applying a calibration equation of the form d_c = function of d_m and h. References **(9)** and **(12)** describe such procedures in more detail, the latter referring to a method for locating the in-focus position of a reconstructed hologram.

Jones' **(10)** hardware modification on a standard 'Quantimet' enabled degree-of-focus discrimination to be performed internally by the form separation module, which normally sorts images according to shape (and hence could otherwise be used to eliminate non-spherical drops). The absence of a peripheral computer also led to the use of a constant value for h' in the focus criterion and to the use of $d_c = d_m = d_2$. Levels I_2 and I_3 were selected in this case to keep d_2 within 2 per cent of the true diameter over the whole range of drop sizes of interest. With a fixed halo width, the effective depth of field and hence the 'sampled' volume were found to increase with decreasing drop size for the smaller drops, requiring weighting corrections to be made to the measured size spectra (which are available only in drop number 'histogram' form from the 'Quantimet').

Where a new requirement for sizing arises, but equipment such as that described above is not available or its cost cannot be justified, one solution is to build photograph-scanning apparatus with pulse-shaping circuitry. The sequence of digital signals produced can be processed off-line by computer to recognize and size individual images. Sato *et al.* **(13)** described such a system working on two grey levels only (black/white), stressing the recognition logic which enabled them to analyse photographs of transparent drops, for which the shadow images are of annular form. A more convenient solution is to make use of standard television cameras and mini-computers. Toner *et al.* **(14)** have adopted this approach in constructing an analyser for on-line use. It is also restricted to black/white analysis and the on-line requirement made it necessary to incorporate complex software to handle partial drop images at the edge of the TV frame. The microprocessor also had to be programmed in a low-level language (which, however, contributed to fast operation).

The approach of the present authors differs from Toner's in that only off-line analysis was required but it was essential to operate on several grey levels because of the large number of 'out-of-focus' images. The resulting system was intended to use a general-purpose mini-computer programmed largely in Fortran, rather than its own dedicated processor, and also a conventional television camera, rather than high-performance types optimized for low light level, high-speed subject movement, etc.

3 SYSTEM HARDWARE

For completeness, brief details will first be given of the equipment used to produce the photographs in the present application. The 'direct shadow' system comprises either an Optical Works Model 7 argon-stabilized spark-gap light source or a similar but more intense source from Pulse Instrumentation & Controllers, both with a nominal $\frac{1}{4}$ μs flash duration which freezes all motion in the present application. A converging light beam is used to avoid diffraction rings round the images. An MPP monorail camera records on Ilford FP4 127 × 102 mm (5 in × 4 in) film using either a Leitz 50 mm focal length lens or a Componon 80 mm lens, at present with open shutter in a darkened room. With fully extended bellows, giving a distance from lens to film of about 760 mm, magnifications are either 14 × or 9 ×. This requires close proximity of the lens to the focused portion of the flow. To minimize contrast degradation caused both by high drop concentration in the intervening space and by wetting of the glass screen which protects the lens, an air-purged hood is fitted to the lens, its length determined by the need to avoid interference to the flow pattern. No upper limit on drop concentration has yet been determined, but satisfactory photogaphs have been obtained with an average inter-drop spacing of 10 drop diameters. Developing for 3 min in Ilford Contrast FF at 1 : 4 dilution produces negatives with adequate contrast which are used directly in the analysis system.

Illumination of the negatives is by a 12 V quartz iodine lamp with condenser lens and diffusing screen, using direct current to avoid loss of information during the TV scanning. A Sony AVC4600CE television camera with vidicon tube and 80 mm focal length lens scans a selected region of the negative, any partial images on the edge of the frame being manually masked at present. Its video signal is passed to a purpose-built digitizer which divides each of the 625 lines into 384 'picture points', a number consistent with the resolution of the camera. The grid used in practice is restricted to 580 lines (y-coordinates, measured from top of frame) by 380 points (x-coordinates, measured from left of frame). Each point is assigned a grey level on an equal-interval scale from 0 to 7, enabling the level to be represented by three bits. The seven levels are contained within a 'window' which can be stretched or compressed relative to the video signal, either by altering the level 7 voltage or by adjusting the signal level (via the camera lens aperture or video gain). It may also be translated, by subtracting a chosen voltage from the signal. This provides the same flexibility as the very large number of fixed grey levels on a typical commercial image analyser. The digitized information is transferred to a Digital Equipment Corporation (DEC) PDP-11/45 mini-computer (24K 16-bit words); the reading sequence of (x, y) coordinates, determined by the scanning speed and the interlaced scan pattern, is (1, 1), (1, 3), (1, 5) ... (1, 579), (1, 2) (1, 4), (1, 6)... (1, 580), (2, 1), (2, 3), etc. (The half-line at the beginning of one of the two interlaced scans is masked out.) The grey levels are packed five to a word, gaps being left during the odd scans to be filled during the next even scan so that y-coordinates are stored consecutively. To overcome the apparent requirement for a buffer size of 44 K for a complete frame, logic is incorporated to halt reading when the x-coordinate reaches 128 or 256; software restarts reading after the 15 K buffer, holding data from one-third of the frame, has been emptied. Whereas Toner *et al.* (**14**) concluded that a 16-bit word length was essential because the coordinates of a picture point require at least nine bits, the present system avoids this requirement by not storing coordinates at all. Knowing the reading order, the position of a given grey level value in the sequence is later decoded to give the corresponding coordinates.

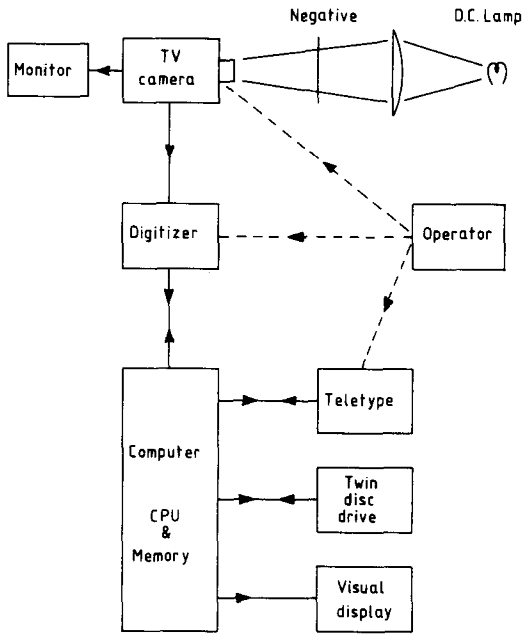

Fig. 2. Block diagram of image analysis hardware

A DEC RK05 disc is used to hold the data from up to 24 frames for subsequent analysis (the number of frames making up one photographic negative being determined by the overall magnification required to size with sufficient accuracy the smallest drops of interest). The data can be recalled at any time to display on a video monitor (Tektronix 611) the detected images at or above any desired grey level, a useful facility in cases where there is some doubt as to how the system will interpret certain features on the negative, such as areas of markedly different background intensity.

A block diagram of the system hardware is shown in Fig. 2.

4 IMAGE ANALYSIS SOFTWARE

A much reduced data file is created from the binary grey level map by a routine which records, for each grey level required, only the coordinates at the ends of each segment of a scan line in which the digitized intensity is at or above that level; this is known as run-end coding (Rosenfeld (**15**)). The technique developed for recognizing individual drop images, or 'cells', is a combination of the best features of two distinct methods. These constitute the scheme of Sato *et al.* (**13**) in which mapping tests are applied across two consecutive run-end-coded scan lines at a time, and the scheme known as a coded chain search (Rintala and Hsu (**16**)). Details are given by Ow (**17**), and will be the subject of a later paper. Ow describes the treatment of isolated short segments which appear in the background and also within cells (especially where the video peak of an image just skims one of the grey levels). Procedures are included for detecting and filling in the voids within cells, which result both from such random breaks in detection at the particular grey level and from the dark spot (on a negative) at the centre of an image of a transparent drop. The algorithm is capable of detecting cells within cells and separating them, and hence may be used on more complex images than those of liquid droplets.

Following the cell recognition routine, the blurred images are rejected. As a result of the calibration described in Section 5, the criterion selected for discriminating between 'in-focus' and 'out-of-focus' images is a constant value of h' (see Section 2) for a given magnification.

Although the incidence of significantly non-circular images is low in the present application, a routine is included which evaluates the area A and perimeter P of each cell (in picture points) and then discards any cells having a shape factor P^2/A greater than a pre-set value. (A circle has the minimum possible value of $P^2/A = 4\pi$. Because P is evaluated by counting the picture points on the image periphery, the pre-set value allows for this approximation.) This also eliminates any scratches on the negatives. A scale factor is then applied to the cell areas A_3 at intensity I_3 (chosen from the calibration), to convert them to true projected areas of the drops. The factor is found in advance from digitizations of horizontally- and vertically-positioned photographs of a precision microscale (taken at the same time as the drop photographs). Each drop image is assigned a diameter calculated as $(4A_3/\pi)^{1/2}$, shown by Herdan (**18**) to be the most consistent way of characterizing shapes which are not perfectly circular. Any desired characteristics of the processed frame, or an accumulation of several frames, may then be computed: spectra based on number, volume, surface area, etc; cumulative distributions; various mean diameters. These are currently output on a teletype but graphical presentation on a visual display unit should be relatively simple to add. Partial images at the frame edges (presently masked out) could in principle be included in the processing, and spectra, etc, corrected on the basis of Bockstiegel's work (**19**).

All the analysis routines are written in Fortran IV. PDP-11 assembly language is only necessary for writing and reading the grey level map (because of the compression of five data items into each word) and for driving the video monitor (because it is an analogue device; a visual display terminal with Fortran graphics package would be both easier and faster to use).

5 CALIBRATION AND SYSTEM PERFORMANCE

An example of the video signal variation along a single scan line passing through one large image is shown in Fig. 3(a). Several successive scan lines in Fig. 3(b) show how the intensity falls as the outer edge of a single image is approached. Fig. 3(c) is a typical scan across a drop photograph, cutting several images.

A comparison reticle having discs of various diameters between 10 and 1000 μm was photographed at several positions relative to the plane of best focus, for the purpose of determining the variation of halo width and measured size. Further tests were carried out using circular holes in opaque backgrounds in front of the TV camera. Figure 4 illustrates the effect of altering the peak video voltage (I_1) and the relative position of grey level 7, denoted by I_{1A}, for a photograph of one of the recticle discs. For the size range relevant to the present application (up to 200 μm), the most accurate sizing of the calibration discs was achieved with the following settings (retaining the notation of Fig. 1 where the intensities I are represented by video signal voltage). The peak intensity in the complete frame is now denoted by I_1 and was set at 0·30 V signal level; level 0, representing I_4, was set at the video pedestal position; because of noise, this does not correspond exactly with the mini-

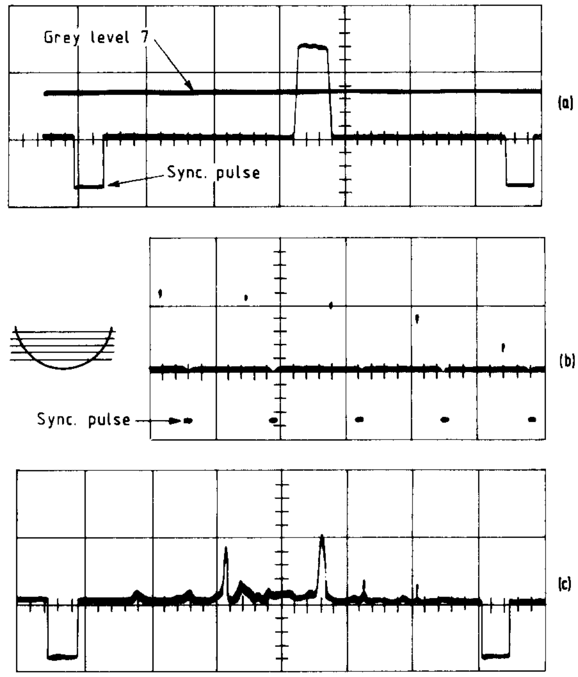

Fig. 3. Video signals across drop images, traced from long-exposure photographs of 100+ successive oscilloscope traces of the same TV line(s). (a) Single line through one large image; (b) Five successive lines approaching lower edge of one image; (c) Single line through several images

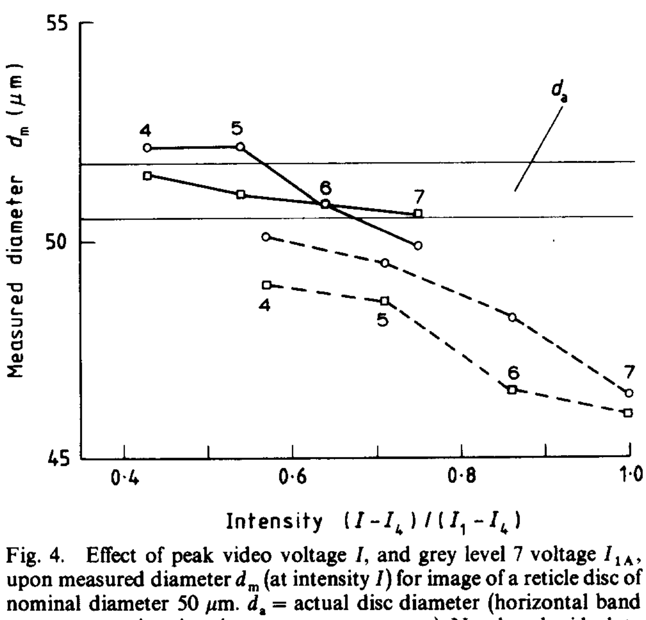

Fig. 4. Effect of peak video voltage I, and grey level 7 voltage I_{1A}, upon measured diameter d_m (at intensity I) for image of a reticle disc of nominal diameter 50 μm. d_a = actual disc diameter (horizontal band covers uncertainty in microscope measurement). Numbers beside data points denote level on grey scale

I_1 = 0·25 V (○) and 0·30 V (□)

$(I_{1A} - I_4)/(I_1 - I_4)$ = 0·75 (——) and 1·00 (- - - -).

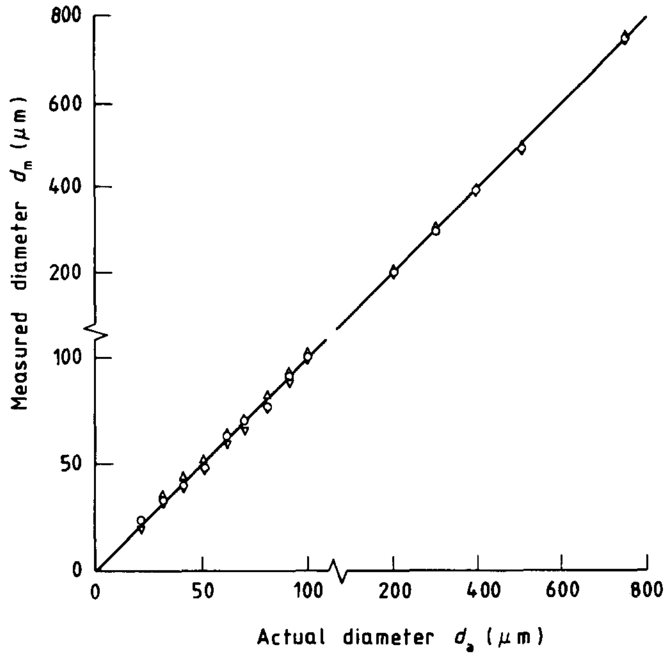

Fig. 5. Comparison of measured and actual diameters for in-focus photograph of reticle discs. (d_a = diameter of disc, not its photographic image; plotted points indicate accuracy of complete measurement process, not the image analysis system alone.)

$(I_{1A} - I_4)/(I_1 - I_4)$: △ 0·57, ○ 0·75, ▽ 1·00.

mum intensity on the negative. Grey level 7, I_{1A}, was set such that

$$(I_{1A} - I_4)/(I_1 - I_4) = 0{\cdot}75 \qquad (3)$$

The disc diameter was then best defined by the value at grey level 4; if this is taken as I_3 in Fig. 1, then

$$d_m = d_3 \quad \text{where} \quad \frac{I_3 - I_4}{I_{1A} - I_4} = \frac{4}{7}. \qquad (4)$$

The overall accuracy of the combined photographic and image analysis system is indicated in Fig. 5.

Figures 6 and 7 show some results for the reticle discs plotted so that direct comparison is possible with ref. **(10)**. It was clear that a maximum halo width in the region of 2 μm could be taken, with reasonable accuracy, to represent a fixed depth of field, regardless of drop diameter. This corresponds with Ramshaw's **(8)** simplified theory and enabled subsequent analysis to be

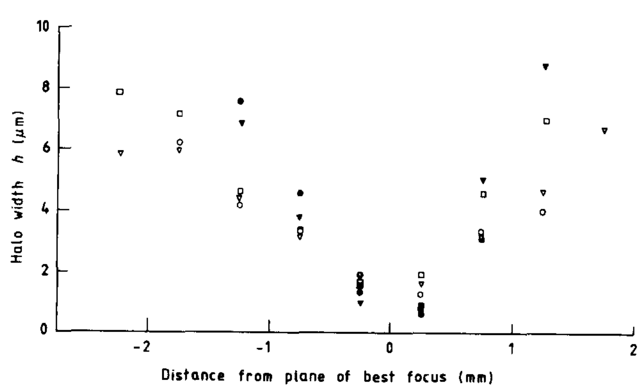

Fig. 6. Variation of halo width h (between grey levels 4 and 5) with position of reticle in field for magnification 9×. Disc diameters in μm: ■ 32, ● 61, ▼ 92, □ 202, ○ 398, ▽ 754

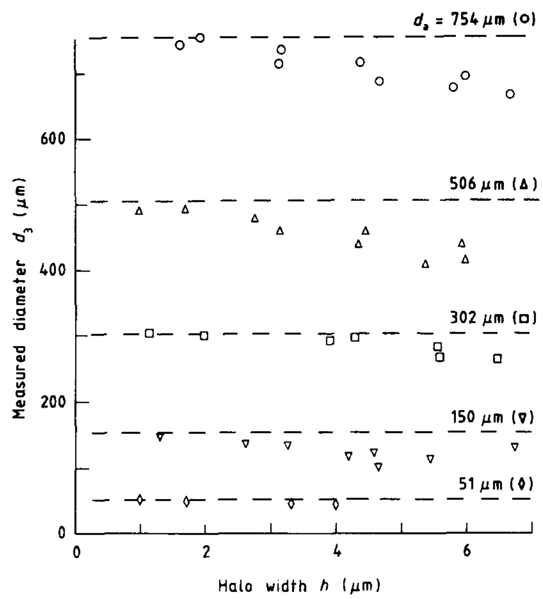

Fig. 7. Relationship between measured diameter d_3 (at grey level 4) and halo width h (between levels 4 and 5) as reticle is moved relative to plane of best focus. d_a = actual diameter of disc

carried out without the weighting or correction factors referred to in **(9)** and **(10)**. It must be remembered, however, that this is an end result which depends on the image analysis system as well as the photographic procedure. Focus discrimination is therefore based on a constant h' with h defined by grey levels 4 and 5. If these represent I_3 and I_2 respectively, then

$$h = \tfrac{1}{2}(d_3 - d_2) \quad \text{where} \quad \frac{I_2 - I_4}{I_{1A} - I_4} = \frac{5}{7}. \qquad (5)$$

Also $d_c = d_m$. Values of h' are 1·5 μm for photographs with ~14× magnification and 2·0 μm for ~9×. The corresponding depths of field are approximately 0·25 mm and 0·50 mm respectively. Plotting intensity gradient as a 'local' value between grey levels 4 and 5, or as an averaged value between levels 4 and 7, was found to give very similar results, implying approximately linear intensity variation at the image edges; this choice of h is therefore arbitrary.

Whereas the calibration results referred to so far were obtained with a peak intensity I_1 appropriate to a high-quality photograph, further tests have shown how d_3 and h are related when I_1 is altered (via TV camera lens aperture) to simulate photographs with varying contrast. $(I_{1A} - I_4)/(I_1 - I_4)$ was increased beyond 0·75 as far as 1·33 so that the video peaks sank lower through the grey scale, covering the range found in practice for 'in-focus' drop images. While $h \approx 2$ μm was found still to be a reasonably satisfactory focus criterion (provided an excessive number of images was not thereby rejected), the aim has been to maintain the best possible contrast so that all but the smallest images have a peak intensity close to that used to set I_1 for the complete frame.

Figure 8 shows an example of the detected image displays at two different grey levels, indicating the very frequent occurrence of isolated features which represent background intensity variations. These are currently processed by the cell recognition routine in the same way as drop images and are then discarded if they

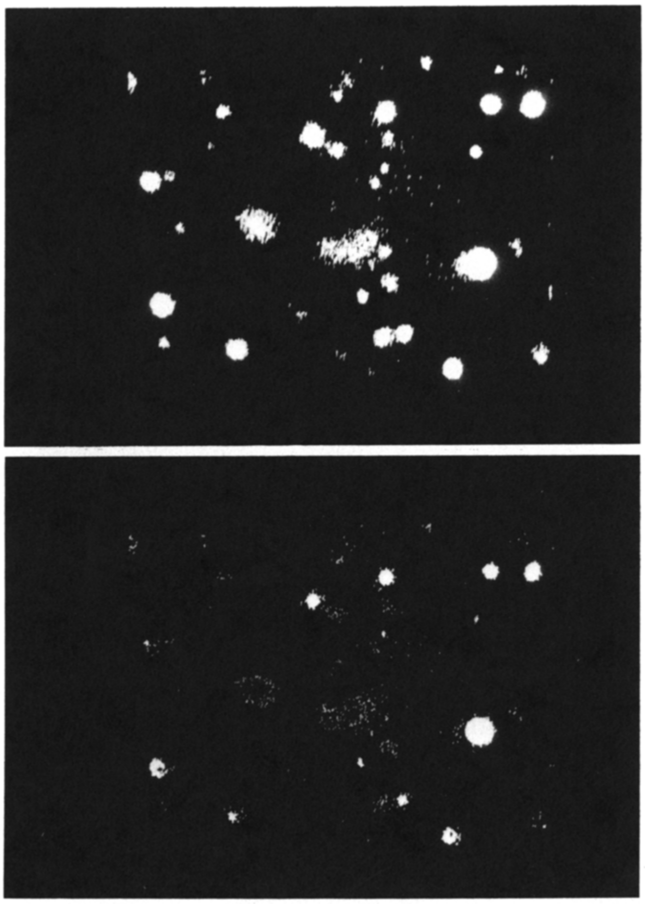

Fig. 8. Typical displays of detected features in a complete frame at grey levels 4 (above) and 6 (below)

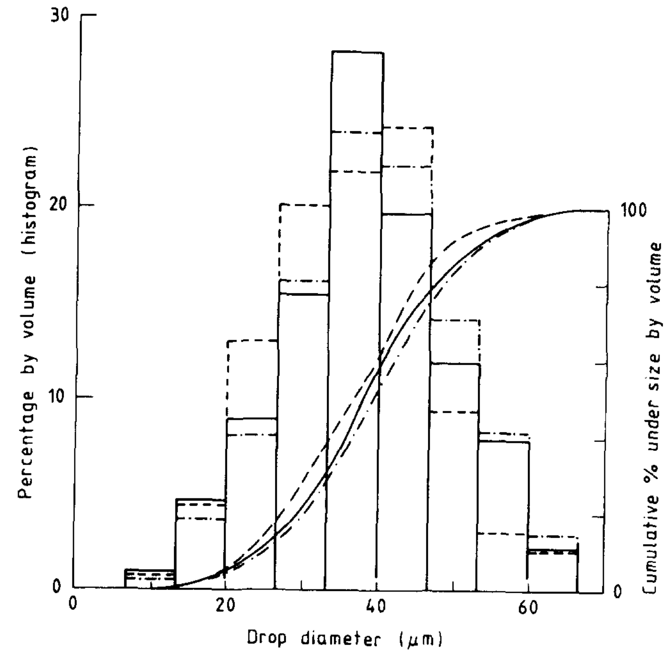

Fig. 10. Drop size distributions from photograph shown in part in Fig. 9. (Approximately 500 'in focus' images).

—— automatic analysis

- - - - manual analysis (observer A)

—·—· manual analysis (observer B)

(Manual sizing was by sorting images into size groups only, followed by calculation of refined distributions by the method of Wise (**21**))

occupy fewer than three scan lines in the y-direction. Results of processing the drop photograph, part of which is shown in Fig. 9, are plotted in Fig. 10. This compares the size distribution with those obtained manually by two different observers and indicates the very satisfactory performance of the system in the present application. It also demonstrates the subjectiveness in manual analyses; consistency achieved when a single observer repeats an analysis can be equally poor.

Two particular errors arise from use of the present TV camera. One is caused by the 1–2 per cent random variation in line scanning speed, which affects picture point spacing since the points are defined by the pulses from a stable oscillator. Repeatability checks have shown that the change in measured diameter, from this effect or any other, never reaches 1 per cent. A potentially more serious effect occurs when an image is moved across the field of view of the camera; for an image occupying about 6 per cent of the frame area, a series of measured diameters d_3 (at grey level 4) covering all parts of the frame had a standard deviation of 2 per cent of their mean. Provided the calibration takes this variation into account by careful choice of image position in the frame, the net effect on a 'production' run will be small when a sufficiently large number of images is analysed, having random positions on the negatives. Since image areas are computed by summing rectangular areas, the overall error in sizing increases as the image size is reduced. (In a typical case, a 300 μm drop photographed at 9× magnification is televised to give an image area of just over 3000 picture points, so that a 30 μm drop would be represented by about 30 points only.) There is additionally an uncertainty of 1 per cent in diameter resulting from estimation of the true area corresponding to a single picture point. However, as with a commercial analyser, it is not practicable to assess the overall error from consideration of all the contributing factors; only the end results from a calibrated system, such as Fig. 10, can indicate the degree of confidence which can be placed in the analyses.

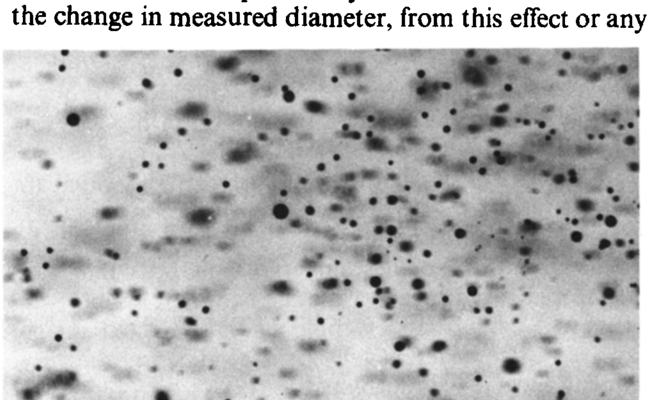

Fig. 9. Part of typical drop photograph. (Area = approximately 6 per cent of complete negative)

Comparisons of the speed of operation of the present system with those of 'Quantimets', for example, are not yet meaningful. Although the minimum analysis time for one TV frame is currently about 10 min (compared with 3 min for the system of (**9**)), developments in three areas could make a substantial improvement. First, it has been found that fragmentation of drop images near their peak intensity and background intensity fluctuations give rise typically to four times as many detected features (cells) at grey level 5 as at level 4; this dominates the processing time and requires an improved recognition algorithm to eliminate irrelevant cells at an earlier stage. Second, a finer grid of picture points would allow larger areas of negative to be televised in one frame without losing accuracy and resolution; a digitizer working on a 576 × 1024 grid and with 16 grey levels (**20**) has already been developed from the present version, but must be matched with a higher resolution TV camera. Third, the use of cartridge discs for intermediate data storage has an extremely adverse effect on running time; a computer with sufficient core or semiconductor memory would solve this problem, or else the matrices of grey levels could be transferred via magnetic tape to a large computer for subsequent processing if the quantity of accumulated frames made it worth while.

6 CONCLUSIONS

An off-line automatic image analyser with detection at eight grey levels has been successfully built round a conventional television camera and a minicomputer. Automatic analysis has thereby proved feasible where the cost of proprietary equipment was prohibitive and reliance on the few remote installations known to have the necessary capabilities was unsatisfactory for development work.

Software developed for the system includes a new algorithm for recognizing relevant images, regardless of shape, and performing subsidiary operations such as filling in internal voids, without the operator intervention which proprietary analysers commonly require.

In its initial application, the system has provided the required resolution and accuracy for sizing liquid drops in the 20–200 μm diameter range from shadow photographs at 9× magnification containing a high proportion of 'out-of-focus' images. Focus discrimination is based on the results of calibrations, the procedure being similar in principle to those recently reported by other workers. Its major advantage over manual analysis has been in providing consistent, non-subjective results, while further development can produce a clearer advantage in speed of operation. Compared with common proprietary analysers, its software-based image processing should offer greater flexibility in areas such as focus and shape discrimination for new applications.

ACKNOWLEDGEMENTS

The present system was developed from a black/white digitization system produced in the Nuclear Power Section of the Mechanical Engineering Department under Dr C. B. Besant. His permission to use the television camera and the computer, his encouragement, and the contributions of his staff and students, particularly Mr D. Thompson, are gratefully acknowledged. Mr R. D. Bloxham is especially thanked for his part in the design and construction of the digitizer.

Extremely useful discussions were held with Dr A. R. Jones (CEGB, Marchwood) and Dr A. J. Yule (Sheffield University).

The work was partly funded by a Science Research Council grant.

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