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A device for producing controlled collisions between pairs of drops

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Abstract—The design and operation of a device for producing reproducible and controlled collisions between pairs of liquid drops in gaseous media is described. Collisions were promoted between uniformly sized, equally spaced drops from two converging streams in a repeated fashion at frequencies ranging up to several thousand events per sec. The size, velocity, direction of motion and position at impact for each drop were independently controlled.

INTRODUCTION

ANY attempt to experimentally investigate the phenomena which occur when freely moving drops collide is generally frustrated by such difficulties as controlling, reproducing, quantitatively measuring and, in some cases, even observing such events. Various techniques have been devised which have alleviated certain aspects of these difficulties but in no case have all of the problems been solved. In order to better study the nature of collisions between pairs of drops, an apparatus has been developed which will, under predetermined ambient conditions, produce repeated and controlled events. The details of the construction and operation of this device are the subject of this paper.

METHODS FOR PRODUCING STREAMS OF UNIFORM DROPS

Streams of uniformly sized drops in gases were produced as early as 1833 by SAVART [1]. He found that the break-up of a jet of liquid issuing from an orifice was so influenced by the impact of the drops on the mechanical support which held the orifice that the jet disintegrated quite regularly. Each equally spaced drop was the same size as its predecessor and exhibited the same oscillatory motion, thereby allowing all motion to be "stopped" by intermittent viewing which was synchronized with the break-up. Later in the century. RAYLEIGH also studied this phenomenon and carried out most of the early theoretical work related to it [2]. This and later theoretical work on the break-up of jets of liquid has been summarized by MIESSE [3]. RAYLEIGH was probably the first to produce repeated collisions between two streams of regularly spaced drops. He collided drops of about 2·5 mm dia. from two jets fed from a common supply tank. Regular disintegration was caused by vibrations from a tuning fork which transmitted regular disturbances to the jets through the tank [4]. RAYLEIGH later noted that vibrations for regularized break-up could be conveniently supplied by a telephone diaphragm [5].

Half a century later when practical needs for uniformly sized drops arose, numerous devices were developed for producing streams of such drops. DIMMOCK [6] produced streams of primary and subsidiary drops, 10–300μ in dia., by vibrating fine glass capillaries of about 0·025 in. o. d. and up to 8 in. long. Drops of different size were thrown off at different points on the path traced by capillary tip, usually at points of maximum acceleration, with each size following its own trajectory. A particular stream could be selected by shielding off all streams except that which was desired. The vibrations were induced by a 60–cycle electromagnetic field acting on a steel sleeve around the capillary and the capillary was broken to its resonant length. VONNEGUT and NEUBAUER [7] produced drops, 16μ in dia. and larger, by a similar technique but the capillaries were excited at their natural frequencies with an air jet. The number and size of drops were determined by the position of the air nozzle, the air velocity, and the dimensions of the capillary. A different capillary was generally used for each desired size of drop. Capillaries for producing small drops were operated at frequencies of up to several thousand cycles/sec. DAVIS [8] produced uniform streams of drops of oil, 6–140μ in dia. by a somewhat different vibrational technique. A metal "finger", supported on a cantilever and vibrated at 60 c/s by an electromagnet such that the amplitude of the motion was variable, periodically contacted a torus of liquid which formed around the tip of a nozzle. On each contact the "finger" drew out a ligament of liquid which contracted into a drop. Size variation was obtained by changing the size of the nozzle and the rate of flow. An elaboration of this technique by RAYNER and HURTIG [9] gave drops of oil of 70–400μ in dia. In this case the "finger" was vibrated in a sinusoidal fashion at a frequency of 10–100 c/s. Two oppositely directed trains of drops resulted from filaments drawn out from the torus of liquid formed around the tip of a hypodermic needle. Size was determined mainly by the rate of flow but was also influenced by the frequency and amplitude of vibration. RAYNER and HALIBURTON [10] later improved on this method by substituting a horizontal rotating blade for the vibrating "finger" and obtained drops of oil and aqueous solutions of 50–700μ in dia. With proper adjustment of the blade relative to the end of the capillary from which the liquid flowed, a single stream of uniform drops was obtained over a range of rates of flow. Drops were produced at rates of 10, 15 and 20 per sec. Size was controlled by the rate of flow and rotor speed.

A different and quite simple method was reported by BLANCHARD [11] which yielded drops of 2–500μ in dia. The drops resulted from a stream of bubbles bursting from the surface of a liquid. As the bubble burst, the crater, which was formed, gave way to a short jet of liquid which necked off into one or more drops. The size of the drops varied with the size of the bubbles. A fast stream of small bubbles could result in a stream of thirty or more droplets being air-borne simultaneously.

MAGARVEY and TAYLOR [12] finally returned to the RAYLEIGH mechanism for producing streams of uniform drops. They produced drops, 0·3–2·5 mm in dia., by axially vibrating squarely honed hypodermic needles with an earphone whose diagram was in direct contact with an elbow in the support which bore the needle. Drops were produced at frequencies of up to 400 cycles/sec. By adjustment of the pressure between the diaphragm of the earphone and the elbow of the support for the needle the satellite drops, which usually occur between the primary drops in RAYLEIGH break-up, could be eliminated. The same investigators also produced trains of large drops with two additional devices that apparently ejected the drops one at a time from differently sized tubes which served as nozzles. One device produced drops. 2·5–10 mm in dia., by transmitting vibrations directly to the liquid with an earphone and the other produced drops, 10–20 mm in dia., by means of a variable-speed motor which delivered periodic shocks to the liquid through a rubber membrane. With this equipment MAGARVEY and GELDART [13] studied collisions between a single large drop and a stream of 10–20 small drops plus collisions between pairs of large drops. These collisions were non-repetitive in nature and occurred under conditions of free fall.

Most recently a device for producing regular disintegration of a jet of liquid has been reported by SCHOTLAND *et al.* [14, 15]. In this device, a tube bearing a hypodermic needle was attached to the diaphragm of a loud-speaker and vibrated transverse to the axis of the needle. Drops, 0·2–1·0 mm in dia., were produced by using squarely honed needles, 20–31 gauge, cut to their resonant length. Collisions were promoted either with a stationary target of liquid [14] or, in a repetitive fashion, with drops from another, identical generator [15]. Other than RAYLEIGH, it appears that only SCHOTLAND and MAGARVEY have used their equipment to produce collisions between pairs of freely moving drops.

The break-up of a jet of liquid is clearly superior to the other methods for producing streams of uniformly sized drops of liquids of low viscosity in that it permits better control over the direction and velocities of the drops, and it is also more versatile and convenient for colliding pairs of drops. Further, this mode of forming drops can be expected to yield drops whose oscillations are more regular, to allow easier control over the size of the drops produced, and to give greater continuity of operation and, in general, more orderly and predictable results. A disadvantage of this method is that primary drops of less than 200μ in dia. are difficult to produce. The present apparatus uses this technique to generate drops and combines all of the advantages previously reported for similar devices [12–15]. Further, this apparatus is not bulky and collisions can easily be produced in a chamber which may be sealed to permit control of the ambient conditions. Also, it is possible to control the size, velocity, position and direction of each drop at impact over a considerably greater range of variables than heretofore reported. The plane in which the collisions occur is independent of the operating conditions. Finally, when a drop experiences a collision before its oscillation has damped out, some control over the shape and movement of its surface at the point of initial contact is possible.

Description of Apparatus

The chamber in which collisions between pairs of drops occurred also acted as the supporting device for the tubes from which the jets of liquid issued as indicated by Fig. 1. The chamber proper

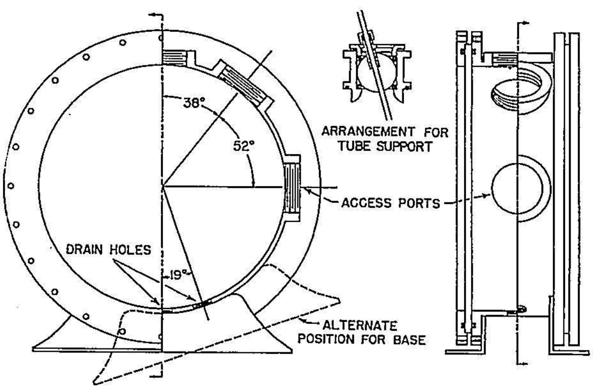

Fig. 1. Construction details of Collision Chamber.

was fabricated from a $4\frac{1}{2}$ in. length of 12-in. steel pipe and was equipped with an adjustable base, drain holes and access-ports as shown. Plate glass windows, whose effective diameters were nearly that of the chamber, were installed at both the front and back of the chamber. All parts susceptible to corrosion were nickel-plated and all access-ports plus the windows were sealed by means of rubber "O" rings.

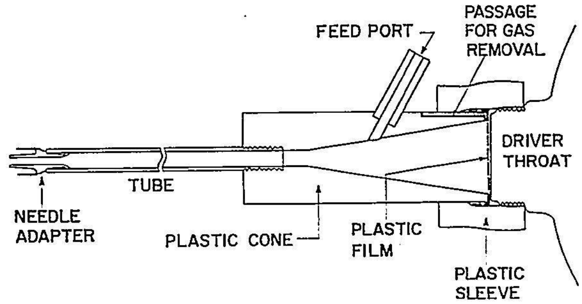

Fig. 2. Arrangement for transmitting vibrations to jet.

The streams of drops were produced from jets of liquid flowing out of squarely honed hypodermic needles. The needles ranged in size from 13–30 gauge, with inside diameters from 1·82–0·160 mm and lengths from 21–4 mm. Matched pairs of twelve of the sizes were prepared. The needles were affixed, by means of modified adapters for hypodermic needles, to the ends of two stainless steel tubes whose length and inside dia. were 8 in. and 7/32 in., respectively. Each tube passed through a ball-and-socket arrangement, as shown, which could be inserted into any of the five access-ports. The ball was a 2-in. aluminium-bronze sphere in which the tube was held by means of a compression fitting. This arrangement coupled with the locations of the access-ports and the alternate positions for the base permitted the needles to be located at varying distances apart and oriented at angles of 30–180 deg relative to each other. Relative angles of 10 deg and less can be obtained if curved tubes are used. The actual angle between the streams at the point of collision is less than that between the needles, especially at the lower rates of flow, because of the effect of gravity on the trajectories of the drops. The unused access ports were sealed off.

The manner in which controlled vibrations were transmitted to each jet is shown in Fig. 2. The tube bearing each hypodermic needle was screwed into the apex of a cone, fabricated from acrylic plastic ("Lucite"), which tapered from an inside diameter of 7/32–1 in. in a distance of $2\frac{1}{2}$ in. The mouth of the cone was held against the throat of a 60-W sonic driver by a thick -walled, tightly fitting sleeve of plasticized polyvinyl chloride ("Tygon"). The vibrations were transmitted by the driver to the liquid through a film of polyvinyl acetate which was

0·012 in. thick, and which was located between the mouth of the cone and the throat of the driver. A passage, 1/32-in. in diameter, permitted the removal of any trapped gases and facilitated the complete filling of the cone and tube with liquid. All liquids were degassed to prevent bubbles from accumulating in the cone and tube. Liquid was fed to the system through a 1/8-in. port on the side of the cone.

The drivers were driven by the sinusoidal output of either the same or two different audio oscillators through 25-W high-fidelity amplifiers. Each driver was separately mounted to minimize transmission of disturbances from either unit to the chamber in which the collisions occurred or to each other. The outputs of the amplifiers were monitored as needed with an oscilloscope to guarantee that nondistorted signals were fed to the drivers. The break-up of the jets and the collisions of the drops were viewed with the aid of a stroboscope. A horizontally mounted low-power microscope was sometimes used to aid in viewing the smaller drops.

PERFORMANCE CHARACTERISTICS

In accordance with the theory for the break-up of laminar jets of inviscous fluids [2] the wave length of the axially symmetric disturbance to which the jet is most unstable was predicted to be 4·51 times the dia. of the undisturbed jet, and this wave length should predominate when a number of disturbances of different wave lengths and equal intensities are imposed on the jet. However, when disturbances of different wave lengths and different intensities are imposed on the jet, it is expected that any wave length (within certain limits) whose intensity is decidedly greater than those of the others will control the break-up. This is the principle upon which the apparatus was based.

This technique for promoting the controlled break-up of a jet was studied in detail for vertically moving jets of water in order to determine the rates of flow and frequencies of disturbance for which a high degree of regularity could be expected for a specific size of hypodermic needle. The drops were viewed at a point far enough distant from the point of break-up, so that any oscillations were completely or nearly damped out. Regularity of break-up was judged by the clarity of the combined images of successive drops when viewed at a fixed point in the stream of drops with a stroboscope. Typical results are shown in Fig. 3. The operating regions

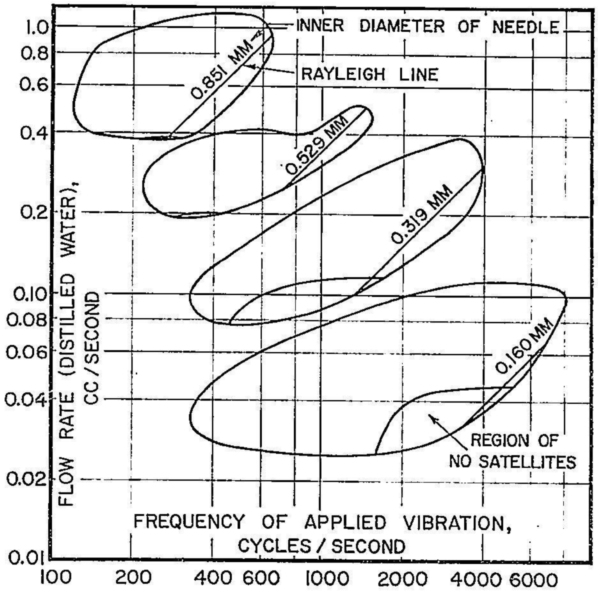

FIG. 3. Regions of regular jet break-up for different needle sizes.

for some of the intermediate sizes of needles are not shown for purposes of clarity. Also, the results obtained with a number of larger needles have been omitted because the greater complexity of the oscillations and the greater distance needed for the oscillations to damp out made the larger drops impractical for study in the chamber.

The peripheries of the regions shown do not represent sharp boundaries. Generally, for each region, regularity of break-up deteriorated slowly as the frequency decreased with the singly formed drops giving way to groups of drops. At the higher frequencies the boundaries were sharper with the break-up becoming irregular just below those rates of flow and just above those frequencies which corresponded to the wave length of the disturbance to which the jet was most susceptible. The straight line in each region corresponds to this wave length of maximum instability and is here called the RAYLEIGH line. The plotted lines are based on jets whose diameters are equivalent to 0·87 of those of the needles themselves; i.e. the standard contraction of a laminar jet was assumed. The small enclosed area at the bottom of each region locates the conditions under which no satellite drops were formed. In this area single primary drops were formed at the frequencies of the applied vibrations and the ligament between the departing drop and the jet drew back into the jet once the drop was free, rather than separating from the jet to form a satellite drop.

In the neighborhood of that part of the RAYLEIGH line located outside the satellite-free area, single satellite drops were formed between the primary drops and their size increased with distance to the left of the RAYLEIGH line. Lines of constant size for both the satellite and primary drops could be drawn parallel to the RAYLEIGH lines. These lines showed a shift to the right relative to the RAYLEIGH line as the size of the needle was increased; e.g., the line for satellite drops which were 1/5 the dia. of the primary drops was found to occur well to the left of the RAYLEIGH line for the 0·160-mm needle, quite close to RAYLEIGH line for the 0·416-mm needle, and well to the right of the RAYLEIGH line for the 0·851-mm needle. Near the RAYLEIGH line the satellite drops consistently exhibited a negative velocity relative to the primary drops which resulted from the ligament detaching from the departing drop before it broke off from the jet. Departure from this region near the RAYLEIGH line not only resulted in larger satellite drops but decreased their negative velocity relative to the primary drops until a reversal point was reached beyond which the satellites exhibited a positive velocity relative to the primary drops. The negatively and positively directed satellites generally collided with the adjacent primary drops and either rebounded or coalesced. If the relative velocity was substantial, as it was near the RAYLEIGH line, coalescence upon initial contact was probable.

Figure 4 shows the ranges of sizes and nominal velocities of drops obtained with a few of the needles studied. These results are based only on the satellite free regions and the regions near the RAYLEIGH lines where the satellites were found to consistently coalesce with the primary drops upon the first collision at the ambient conditions in the laboratory. The nominal velocity was the average velocity of the liquid at the tip of the needle as calculated from

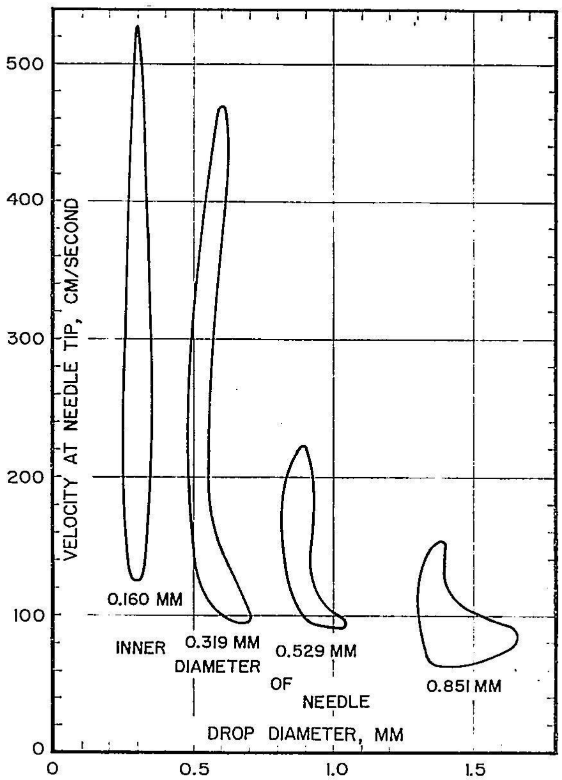

FIG. 4. Drop size and velocity ranges for different needle sizes.

the measured rate of flow and measured inner diameter of the needle. The Reynolds numbers corresponding to the peak velocity showed some scatter but generally fell between 1000–1800. The actual velocities of the drops at the point of break-up, as determined by measuring the distance between stroboscopic images at a known frequency of drop production, varied both above and below the correponding nominal velocities.

As indicated by Fig. 4, the primary drops produced for studying collisions in the chamber ranged in size from 0·25 mm to about 1·65 mm. However, the satellite drops ranged in size down to 0·05 mm in dia., this size being obtained with the smallest needle. While the motion of the satellites which escaped coalescence was usually much less regular than that of the primary drops due to bouncing, it was found that the satellites produced at the reversal point could sometimes be used for controlled collisions with drops from the other stream. In this way the disadvantage of the method due to the previously mentioned minimum size of the primary drops is partially alleviated.

The influence of changing the angle of the jet away from the vertical on the ranges of flow and frequency for regular break-up was also noted. For jets of large dia. the minimum flow, at which regular break-up occurred, increased as the jet became more horizontal. This would tend to raise the bottoms of the two regions shown in Fig. 3.

Oscillation of the drops was controllable to a certain degree. The oscillations produced in the drops were identically repeated by each drop but were not necessarily axially symmetric, even when the jet was vertical. With nonvertical jets a spin was commonly added to the oscillation of the drop. However, when axially symmetric oscillations did occur, it was possible to measure the maximum and minimum diameters of the oblate and prolate forms, thus making possible a prediction of the instantaneous velocity at the surface of the drop by means of available theory [16].

One difficulty, which has been experienced and which has perhaps been shared by other experimenters, was that regular break-up of a jet could be impeded by any of a number of factors such as particles lodging or bubbles of gas forming in the needle.

Illustrative Results

To illustrate the effectiveness of this apparatus in promoting controlled and, in particular, repetitive collisions between pairs of drops, three photographic sequences involving collisions between drops of distilled water in the normal atmosphere of the laboratory are presented.

Figures 5 and 6 show a number of consecutive frames from high-speed motion pictures which were taken of colliding pairs of drops. These pictures were taken with a Wollensak Fastax camera which was operated at a nominal speed of 7000 frames/sec. However, for the purpose of illustration, the frames shown were taken from the initial portions of the films where the framing rates were about 3300 frames/sec. The drops were illuminated by backlighting with a photo flood lamp and the light was filtered with a $CuSO_4$ solution. An aperture located between the drops and the lamp reduced the field of the light source to give the drops their dark outlines.

In Fig. 5 are shown repeated collisions between pairs of equally sized drops whose diameters were about 0·77 mm. The drops were moving along their trajectories at velocities of 110 and 120 cm/sec for the left and right streams, respectively. The collisions occurred at a rate of 400 events/sec, the included angle between the trajectories was 15 deg, and the relative horizontal velocity for each colliding pair was 30 cm/sec. These drops were formed from jets which issued from 22 gauge hypodermic needles at rates of flow which were low enough to promote break-up in the satellite-free region. In Fig. 6 are shown repeated collisions between pairs of differently sized drops. The drops at the left were 0·85 mm in dia. and were moving along their trajectory at a velocity of 157 cm/sec while the drops at the right were 0·62 mm in dia. and were moving in their trajectory at a velocity of 113 cm/sec. In this case the collisions occurred at a rate of 520 events/sec, the included angle between the trajectories was 22 deg, and the relative horizontal velocity was 51 cm/sec. These drops were formed from jets produced with a 21 gauge needle for the larger drops and a 24 gauge needle for the smaller drops.

Finally, in Fig. 7 is shown a composite of a number of high-speed photographs, each taken from a separate event in a series of identical collisions. These particular photographs were taken through a low-power microscope with a Graflex Speed Graphic camera equipped with a Polaroid attachment, and very high speed (3000 ASA equivalent), type 47, Polaroid film was used. A stroboscopic light provided the means for selecting the approximate stage of collision by "stopping" the motion as well as the necessary light to expose the film. In this photographic sequence the stroboscope was operated at 2600 flashes/min in conjunction with a shutter speed of 1/50 sec for the camera which allowed the film to be exposed only once per photograph. At this speed flashes with an intensity of 1·2 million c.p. and a duration of 1·2 μ sec were produced. The collisions shown in this sequence were quite similar to those shown in Fig. 5, and the approximate times given for each stage of collision were based upon measurements taken from that high-speed motion picture. These

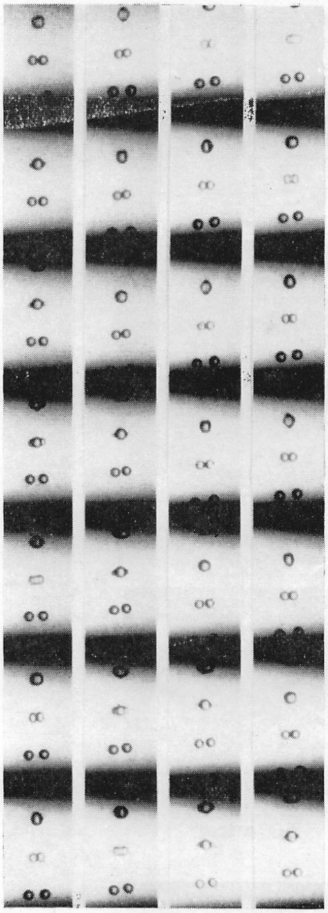

FIG. 5. Repeated collisions between equally sized drops.

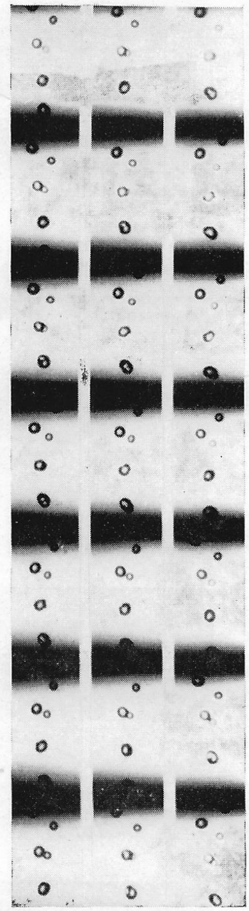

FIG. 6. Repeated collisions between differently sized drops.

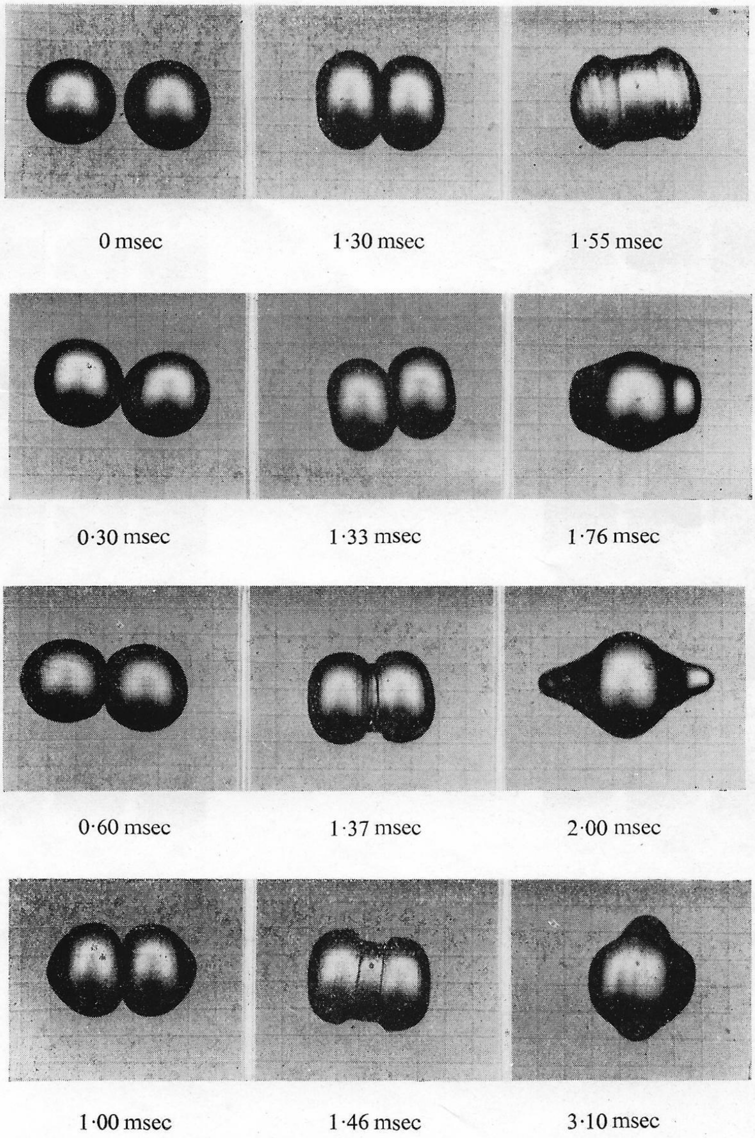

FIG. 7. Stages of a collision between drops (grating lines are 0·234 mm apart; each stage from a different collision).

collisions differed from those in Fig. 5 in that the drops were 0·75 mm in dia., the collisions occurred at a rate of 460 events/sec, the velocities along the trajectories were equal at 92 cm/sec, and the relative horizontal velocity for each pair of drops was 37 cm/esc.

The use of high-speed photographs permitted a more detailed study of the nature of a collision between a pair of drops under specific conditions. As seen in Fig. 7, the manner in which the drops deformed and the nature of the surface waves, which developed after coalescence, are readily discernible. Also, the approximate instant of coalescence is more easily detected; in this case a bridge was formed between the two drops after 1·30 and before 1·33 msec of the timing sequence. The initial stages of coalescence, as shown here, were quite similar to those recently published in the form of some excellent high-speed motion pictures showing the coalescence of drops of water, 2 mm in diameter, which were supported on wires [17].

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