

An experimental study of the flow of thin liquid sheets in hot atmospheres

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A study has been made of the flow and disintegration of thin liquid sheets in combustion gases up to temperatures of 950 °C. It is found that below 300 °C sheet breakdown occurs through the growth of antisymmetric Kelvin–Helmholtz waves. Above this temperature high frequency symmetric waves and localized disturbances are superimposed on the sheet and disintegration then occurs by the combined action of aerodynamic waves and perforations, the contribution of the latter predominating with increasing temperature. It is demonstrated that the new wave system is electrohydrodynamic in origin, the electric field being generated by the charged species present in the gas. The drop size is found to be critically dependent upon the nature of the disintegration process.

1. Introduction

There is a growing knowledge of the factors influencing the disintegration of liquid streams and a number of relations have been formulated which express the resulting drop size in terms of the operating variables (see, for example, Dombrowski & Munday 1968). However, much of this work has been concerned with the processes of drop formation under normal atmospheric conditions and little is known about the spray characteristics in more extreme environments. The purpose of this investigation has been to examine the flow and disintegration of sheets of water in combustion gases at temperatures ranging up to 950 °C.

2. Experiments

The apparatus was designed to study the mechanisms of disintegration of sheets of water in gaseous environments ranging up to 950 °C. The hot gas was directed down into a 7 in. square, 18 in. high asbestos-lined chamber by an inverted 7 in. square flat flame burner, designed to burn premixed propane and air.

Provision was made for cooling the gases by inserting one or two sets of water-cooled tubes between the burner body and chamber while rectangular ports cut in the sides of the chamber afforded access to the interior for photographic observation and temperature measurement. The stabilizing grid of the burner extended over the full area and comprised a number of $\frac{3}{8}$ in. thick ceramic blocks‡ pinned and cemented together.

† Present address: Shell Research Ltd, Egham, Surrey.

‡ Kindly supplied by Siaps Gas Radiants Ltd, Grand Buildings, Trafalgar Square, London.

Manufacturer's designation	Nozzle type	Velocity coefficient	$K \times 10^{-2}$ (mm ²)
Bray Unijet Miniature Y	Fan	0.81	5.5
Danfoss D 8/45	Swirl	0.79	2.8

TABLE 1. Nozzle details

Experiments were performed with flat and conical sheets produced by fan and swirl spray pressure nozzles respectively. Details of the nozzles are given in table 1. They were positioned in the test chamber to spray vertically downwards and could be located at any desired height below the combustion zone, by a $\frac{1}{4}$ in. feed pipe inserted along the axis of the grid. Water was fed to the nozzles from a pressure vessel by means of compressed nitrogen isolated from the liquid in a flexible bag.

Typical axial temperature profiles normal to fan-shaped sheets produced when water at 25 °C and 78 °C respectively is injected into hot gases at a free-stream temperature of 950 °C are shown in figure 1. Figure 2 shows the results plotted in the form of isotherms.

The liquid temperature at the nozzle was measured by a copper-constantan thermocouple placed just upstream of the orifice, while the hot-gas temperature was measured by a silica-coated platinum-platinum with 13 % rhodium thermocouple with appropriate corrections for radiation losses (Dahl 1962, §IVA).

3. Mechanisms of sheet disintegration in hot atmospheres

The effect of ambient gas temperature on the mechanism of sheet disintegration is illustrated in figures 3–5 (plates 1–3) for fan-shaped sheets over a range of injection pressures. Figure 3 shows typical photographs of sheets formed at room temperature, antisymmetric waves† (see figure 6) being clearly visible and causing breakup at the higher pressures.

Squire (1953) and others have analysed this form of wave and have shown it to be aerodynamic in origin with a rate of growth directly related to the gas density. It would therefore be expected that the wave motion should become less pronounced as the gas temperature is raised. This effect was confirmed for temperatures up to 300 °C, but at higher levels, e.g. 380 °C (see figure 4),‡ the photographs reveal an additional higher frequency wave motion which covers the greater part of the sheet and disintegration now occurs as a result of aerodynamic waves and random perforations. At 675 °C (figure 5) aerodynamic waves are only apparent at the highest pressure and the high frequency wave motion predominates throughout. Perforations become more frequent and the region of disintegration recedes towards the nozzle. The mechanism of drop formation now follows closely

† Following Taylor's (1959) terminology.

‡ Because of limitations of the optical components the field of view could not always incorporate the region of drop formation and the nozzle, and, in order to ascertain the position of the nozzle on the photograph, it was illuminated by an auxiliary tungsten light source.

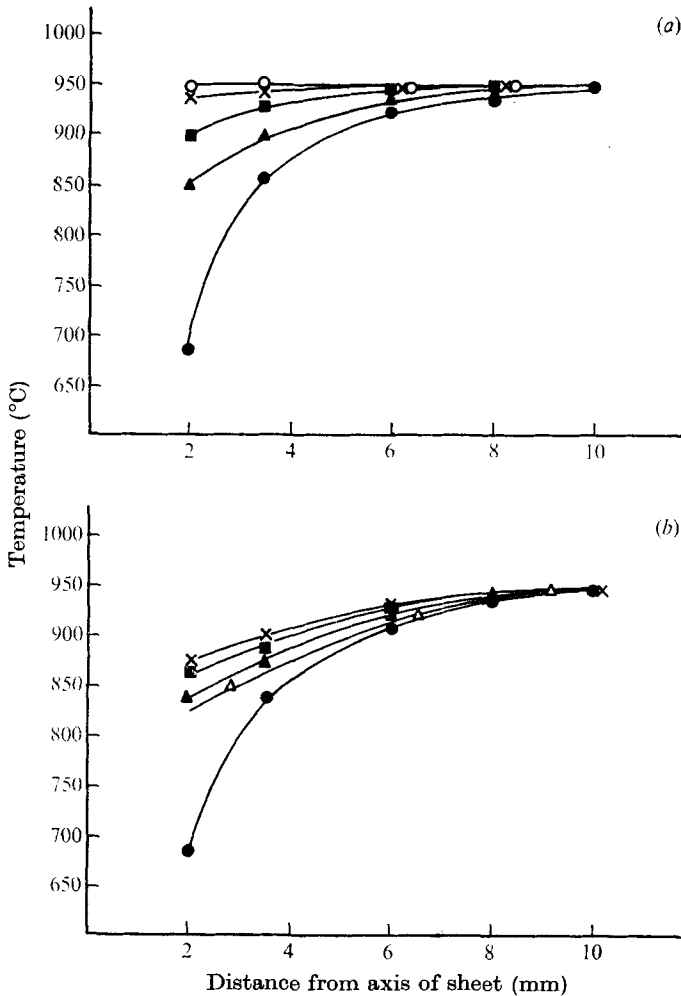


FIGURE 1. Temperature profiles adjacent to a flat water sheet in a hot gas. Bray Unijet Y nozzle, differential injection pressure 1.74 bar. (a) Liquid temperature 25° C, (b) 78° C.

	●	▲	■	×	○	△
Distance below nozzle (mm)	5	10	15	20	25	35

that previously observed for emulsions (Dombrowski & Munday 1968; Andrew, Damani & Dombrowski 1972), where the liquid trapped within a network of holes contracts into ligaments which subsequently break down into a corresponding network of drops. Figure 7 (plate 4) shows part of the sheet illustrated in figure 5 (b). Inspection of the edges of the larger perforations reveals varicose profiles, which indicate the waves to be of symmetric form (see figure 6). This conclusion may also be drawn from the elliptical shape of the perforations, which can be assumed to result from the relatively high rate of expansion along the wave troughs, where the sheet is thinnest. The enlargement also reveals the presence of numerous point disturbances where the waves have high local growth rates. Examination of a large number of similar photographs shows the disturbances

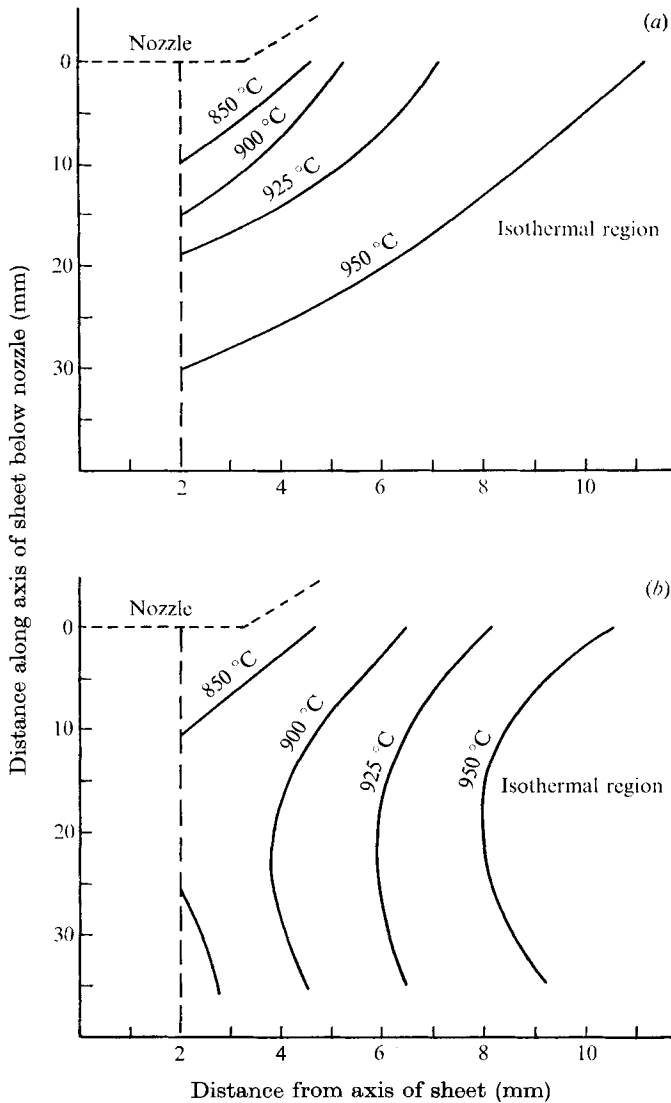


FIGURE 2. Isotherms adjacent to a flat water sheet in a hot gas. Bray Unijet Y nozzle, differential injection pressure 1.72 bar. (a) Liquid temperature 25 °C, (b) 78 °C.

always to be present and randomly distributed about the sheet. This phenomenon was examined further with the aid of a high speed ciné camera operated at a rate of 10 000 frames/s and it was found that disturbances become apparent only at some distance from the orifice and that the sheet perforates only at these locations. Further, measurements made of wave frequency indicate values to be well in excess of the cut-off frequency for aerodynamic wave growth.

A series of experiments was undertaken to ascertain the cause of these phenomena. Initially, in order to determine whether the presence of dissolved air affected the behaviour of the sheet, experiments were carried out with tap water, which was generally found to be supersaturated with air, and with distilled water

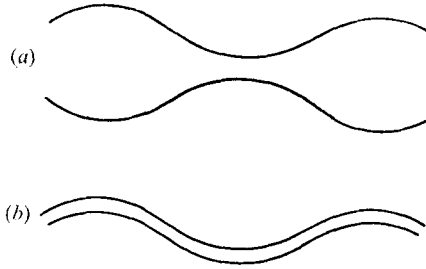


FIGURE 6. (a) Symmetric and (b) antisymmetric wave forms.

in which the air content was reduced to a value of 1 p.p.m. No difference could be detected. Experiments were then carried out in the open laboratory with a Meker burner to examine the sheet more closely. It was discovered that the perforations were produced only when the luminous gases came into contact with the sheet. Since they are a rich source of charged particles, figures in the range 10^{15} – 10^{18} ions/m³ being reported for propane–air flames and 10^{17} – 10^{19} ions/m³ for flames containing traces of alkali metals† (Tsuji & Hirano 1970), it was postulated that the phenomena were associated with the electrical properties of the flame gases.

In order to determine whether charge transfer could take place in the relatively short lifetime of the sheet ($\sim 10^{-3}$ s), a simple apparatus was constructed to determine approximate values of the charge collected by the liquid. Water from a swirl spray nozzle, operated at a low pressure of about 0.7 bar to minimize droplet dispersion, was passed through the impinging flames of two Meker burners and then collected in a perspex container. The bottom half of the latter was covered with a thin copper electrode which was connected through a microammeter to earth. The whole apparatus was surrounded by an earthed aluminium screen. It was observed that, in the absence of the flame, the spray produced a small positive current of approximately 10^{-2} μ A. When the burners were ignited, a negative current of the order of 1–3 μ A was recorded. The negative polarity was not unexpected since it is widely believed (Lawton & Weinberg 1969, chap. 6) that non-emitting surfaces placed in an ionized gas accumulate charge as a result of the high mobility of electrons. However, at this stage, evidence for the waves being electrohydrodynamic in origin was inconclusive since the possibility of temperature effects could not be excluded. Additional experiments were therefore performed to isolate these two properties. The first series was devised to study the behaviour of sheets in hot gases with the spatial charge reduced to negligible proportions, while the second was performed to examine the effect of surface charge at room temperature.

Two approaches were adopted to reduce the spatial charge. The first was concerned with reducing the electron mobility and promoting attachment by introducing a material with a high collision cross-section into the boundary layer. The most convenient method of accomplishing this is to raise the partial pressure

† The ceramic stabilizing grids incorporated in the burners produced predominantly yellow flames typical of sodium traces.

of the water vapour adjacent to the surface by heating the liquid, and a series of photographs was taken of sheets at various temperatures in a gas stream at 950 °C. The partial pressure of water vapour in the combustion gas was estimated to be about 103 mm Hg, corresponding to a liquid temperature of 52 °C, and it was therefore expected that significant effects on sheet stability were only likely to be observed at liquid temperatures above this value. Figure 8 (plate 5) shows photographs of flat sheets of water with temperatures ranging from 56 °C to 78 °C. At 56 °C (equilibrium vapour pressure 124 mm Hg) symmetric wave motion and disintegration typical of that observed at low liquid temperatures is demonstrated. As the liquid temperature is raised, the incidence of perforations becomes less, until, at 67 °C (equilibrium vapour pressure 205 mm Hg), they cease; waves are, however, still evident although the wavelength is increased. As the temperature is raised still further the waves become less pronounced until, at a temperature of 78 °C (equilibrium partial pressure 327 mm Hg), they disappear. Under these conditions the sheet remains plane and disintegration occurs at the edges in a manner similar to that observed by Dombrowski & Hooper (1962) at low densities. Temperature profiles in the test chamber (figure 1) show that the temperatures adjacent to the sheet are not significantly different from those at liquid injection temperatures of 20 °C.

Some observations were also made of the behaviour of conical sheets under the same set of operating conditions. Similar effects were found to occur at low liquid temperatures, but differences were noted at higher values: a few typical results are given in figure 9 (plate 6). At low gas temperatures (figure 9*a*) disintegration takes place through aerodynamic wave motion. However, at high temperatures (figure 9*b*, cf. figure 8) the sheet disintegrates owing to the onset of perforations.

The presence of perforations is not unexpected since under normal conditions a conical sheet produced by a swirl spray nozzle is covered by ripples produced by disturbances originating in the air core (Tahir 1973, private communication) which co-exist with aerodynamic waves. Colbourne & Heath (1950) have shown that these ripples persist at low gas densities when aerodynamic wave motion effectively disappears; the sheet length increases, but premature breakdown by perforations occurs, seemingly as a result of these ripples, before the leading edge attains an equilibrium position. In the light of our findings for flat sheets it was expected that, at high liquid temperatures, conical sheets would exhibit similar phenomena. However, although figure 9(*c*) demonstrates the absence of aerodynamic waves and the presence of perforations, the length of the coherent sheet is smaller than that shown in figure 9(*a*). The cause is revealed by a close inspection of the sheet, which uncovers the presence of high frequency waves although, because of the normally rippled nature of the sheet, they are not so readily identified. The reason for this is not clear, although it is likely that the boundary layers around conical sheets are comparatively thinner as a result of their more turbulent nature and hence the quantity of vapour emanating from the surface at this temperature, may be insufficient to reduce charge diffusion to the surface.

The second approach took advantage of the fact that ionization in hydrogen-air flames is several orders of magnitude less than that in hydrocarbon-air mixtures. A Meeker burner was modified to burn premixed hydrogen and air by

first removing the ceramic grid and placing a fine-mesh stainless-steel gauze in the mouth of the burner. High purity Air Products Ltd gases were used, great care being taken to ensure that all surfaces were free from contaminants. The flame was directed to impinge on both sides of a flat sheet and temperatures of 1300 °C were recorded adjacent to the surface. Stroboscopic illumination showed the sheet to be plane, devoid of both symmetric and antisymmetric wave motion. The two free surfaces contracted owing to surface tension and a sheet similar to that shown in figure 8(c) was produced. Symmetric waves could, however, be induced by seeding the flame with small amounts of sodium bicarbonate.

The effect of surface charge at room temperature was studied by placing an electrode near a flat sheet and causing a high frequency, 12 kV discharge to take place between it and the metal pressing surrounding the nozzle tip. The power source consisted of an Ernest Turner HSS/4/8 stroboscope operating at 4000 flashes/s with the standard flash lamp replaced by a pair of electrodes. The charging mechanism is not directly comparable with that occurring in hot gases, since surface charge will result from both induction and diffusion. However, it was expected that the general characteristics would be similar. A typical result, shown in figure 10 (plate 7), demonstrates the expected pattern of waves and local disturbances, although differences in detail may be observed, the disturbances taking the form of craters.

It may therefore be concluded from these experiments that the new form of instability which we have observed is electrohydrodynamic in origin and results from the accumulation of negative charge at the liquid surface. The observed effects of gas and liquid temperature indicate both the mobility and concentration of the charged species to be significant parameters.

The manner in which these field-coupled waves are initiated has not been examined in detail but an experiment performed with a water bell produced along the lines suggested by Taylor (1959) indicates that the nature of the surface is a further important factor. This form of sheet, resulting from the deflexion of a jet by a rigid flat or conical surface, produces a visually undisturbed stream, and it remained unruffled in the presence of strongly ionized gases. This was an unexpected result since it had previously been reported (Clark & Dombrowski 1972) that, below an orifice Reynolds number of about 9000, sheets produced by Bray fan spray nozzles are also free of disturbances; consequently, symmetric waves should not have occurred with the flow velocities examined in this work. However, the original photographs were carefully re-examined and it was found that weak ripples were in fact present very close to the orifice. Under normal conditions they rapidly decayed, but persisted and grew in a charged atmosphere.

4. Effect of gas and liquid temperatures upon drop size

Flash photographs of sprays produced by the Bray Y nozzle have been used to assess the effect of gas and liquid temperatures upon the volume–surface mean drop size $\Sigma ND^3/\Sigma ND^2$, where N is the number of drops in the size range $D \pm \Delta D$. In general, two measurements were made for each set of operating conditions and the average recorded.

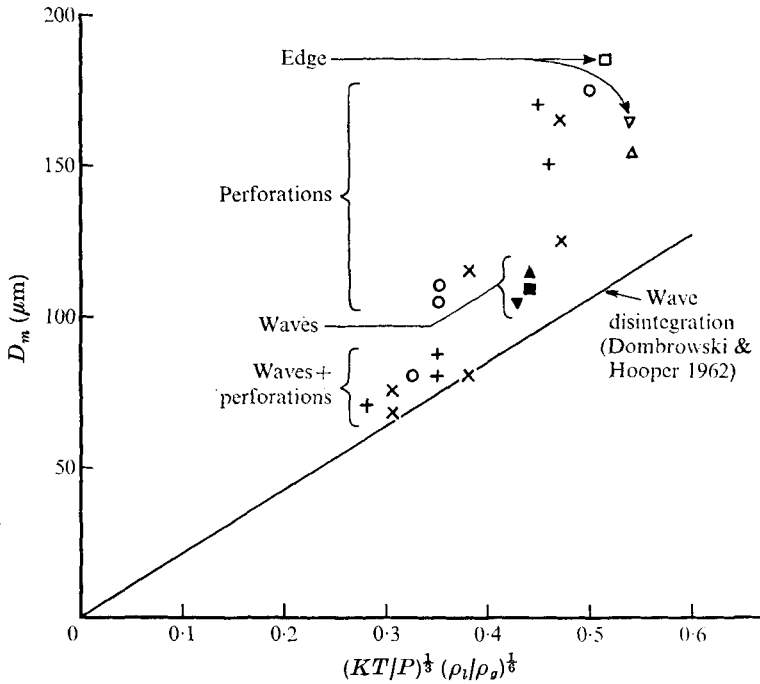


FIGURE 11. Correlation of drop-size data for flat water sheets at varying gas temperatures, showing types of disintegration.

	+	×	○	▽	□	△	▼	■	▲
Gas temperature (°C)	380	675	950	950	950	950	20	20	20
Liquid temperature (°C)	24-28	24-26	22-24	78	67	56	78	67	56

For thinning sheets of low viscosity disintegrating through aerodynamic wave motion, it can be shown (Fraser *et al.* 1962), on the basis of Squire's analysis for parallel-sided sheets, that where the wavelength is large compared with the sheet thickness drop sizes are related to the operating conditions by the following expression :

$$D_m = C \left[\frac{KT}{P} \right]^{1/3} \left(\frac{\rho_l}{\rho_g} \right)^{1/3}, \tag{1}$$

where C is a constant, K is a parameter which relates the sheet thickness to the distance from the origin (Dombrowski, Hasson & Ward 1960), T is the surface tension, P is the pressure differential across the orifice and ρ_l and ρ_g are, respectively, the liquid and gas densities.

The predicted effect of gas density has been confirmed for fan spray nozzles by Dombrowski & Hooper (1962) for densities ranging from 0.3 to 2 kg/m³. Their results expressed in terms of the volume-surface mean diameter were correlated on the basis of (1), giving the value of the constant as 210.†

The results of this study are plotted in figure 11 in a similar manner with the corresponding mechanisms of sheet disintegration identified. The figures show that, where drop formation occurs through aerodynamic wave motion, the results compare favourably with those obtained by previous workers.

† D_m is expressed in μm , K in mm^2 , T in N/m and P in bar.

Where disintegration occurs by perforations the resulting drop size is seen to be independent of gas and liquid temperature or the presence of waves and related solely to the inverse of the pressure. This may be explained by examination of photographs such as those in figure 5 (plate 3), which indicate that the number of perforations increases with pressure. The size of the ligaments is consequently reduced, resulting in relatively smaller drop sizes. The increased frequency is probably due to a greater number of flow disturbances which act as sites of high local growth rate.

Figure 11 also confirms the previous finding (Dombrowski & Hooper 1962) that the breakdown of the rims of the sheet tends to produce drops larger than those caused by wave disintegration.

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REFERENCES

- ANDREW, S. P. S., DAMANI, M. A. & DOMBROWSKI, N. 1972 *J. Colloid & Interface Sci.* **41**, 445.
- CLARK, C. J. & DOMBROWSKI, N. 1972 *Proc. Roy. Soc. A* **329**, 467.
- COLBOURNE, A. J. & HEATH, H. H. 1950 *N.G.T.E. Memo*, M86.
- DAHL, A. I. 1962 *Temperature, its Measurement and Control in Science and Industry*, part 2. New York: Reinhold.
- DOMBROWSKI, N., HASSON, D. & WARD, D. E. 1960 *Chem. Engng Sci.* **12**, 35.
- DOMBROWSKI, N. & HOOPER, P. C. 1962 *Chem. Engng Sci.* **17**, 291.
- DOMBROWSKI, N. & MUNDAY, G. 1968 *Biochemical and Biological Engineering Science*. Academic.
- FRASER, R. P., EISENKLAM, P., DOMBROWSKI, N. & HASSON, D. 1962 *A.I.Ch.E. J.* **8**, 627.
- LAWTON, J. & WEINBERG, F. J. 1969 *Electrical Aspects of Combustion*. Clarendon Press.
- SQUIRE, H. B. 1953 *Brit. J. Appl. Phys.* **4**, 167.
- TAYLOR, G. I. 1959 *Proc. Roy. Soc. A* **253**, 289.
- TSUJI, H. & HIRANO, T. 1970 *Combustion & Flame*, **15**, 47.

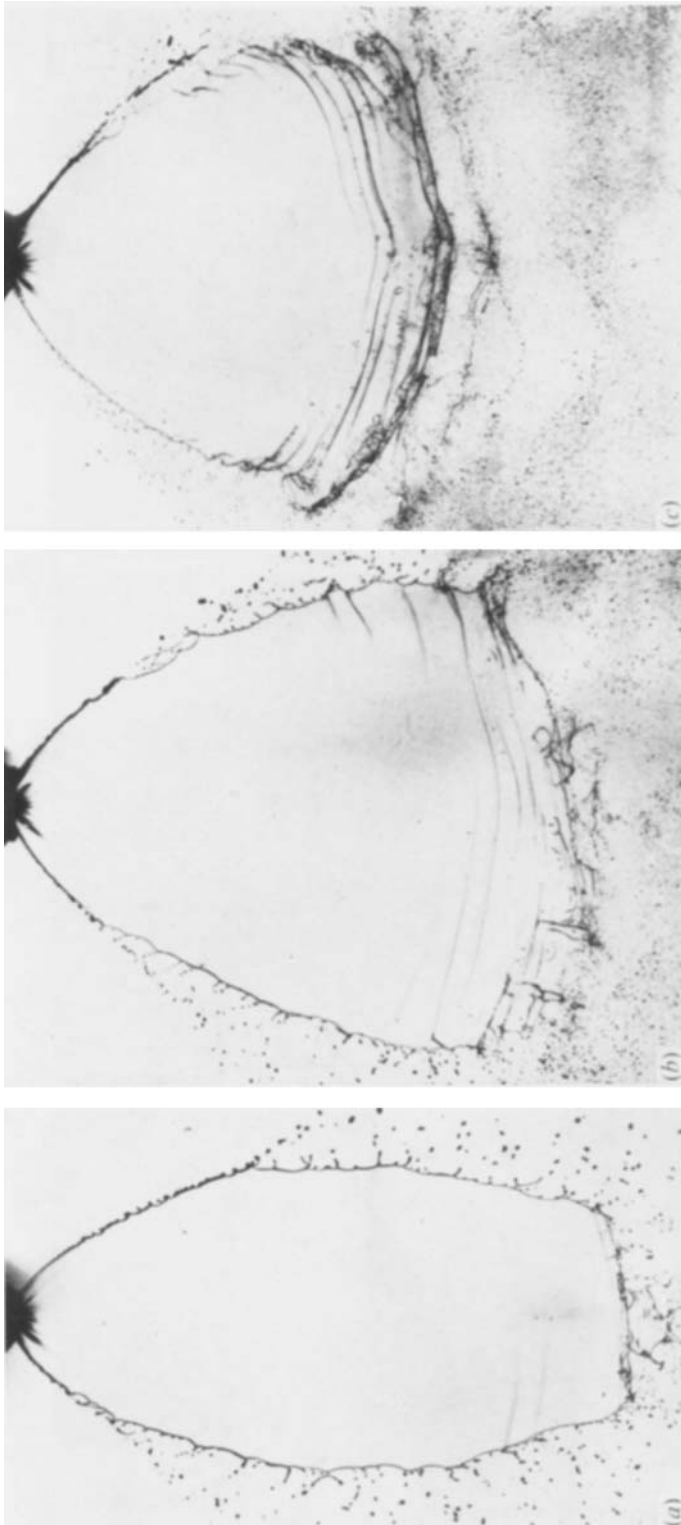


FIGURE 3. Wave formation on flat water sheets at room temperature; magnification $\times 1.7$. (a) 1.72 bar (25 lb/in.²), (b) 3.44 bar (50 lb/in.²), (c) 6.2 bar (90 lb/in.²).

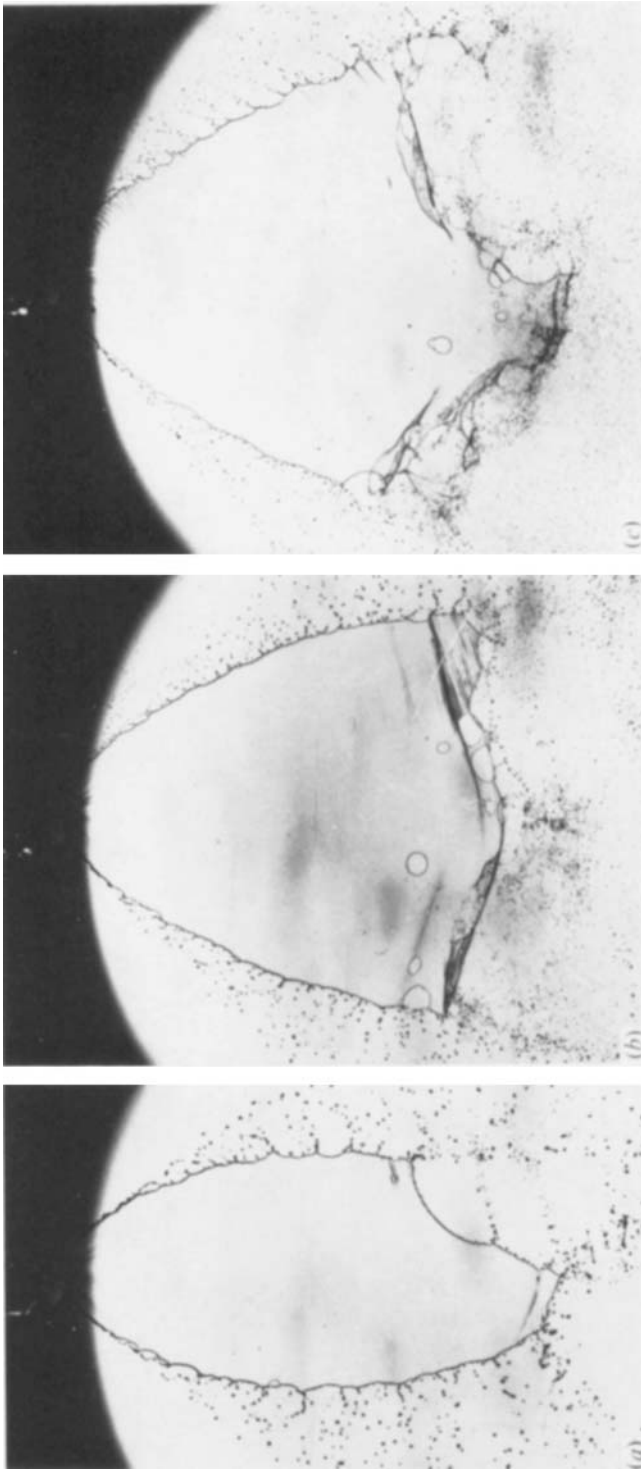


FIGURE 4. Wave formation on flat water sheets at a gas temperature of 380 °C (liquid temperature 24–28 °C); magnification $\times 1.7$.
(a) 1.72 bar, (b) 3.58 bar, (c) 6.35 bar.

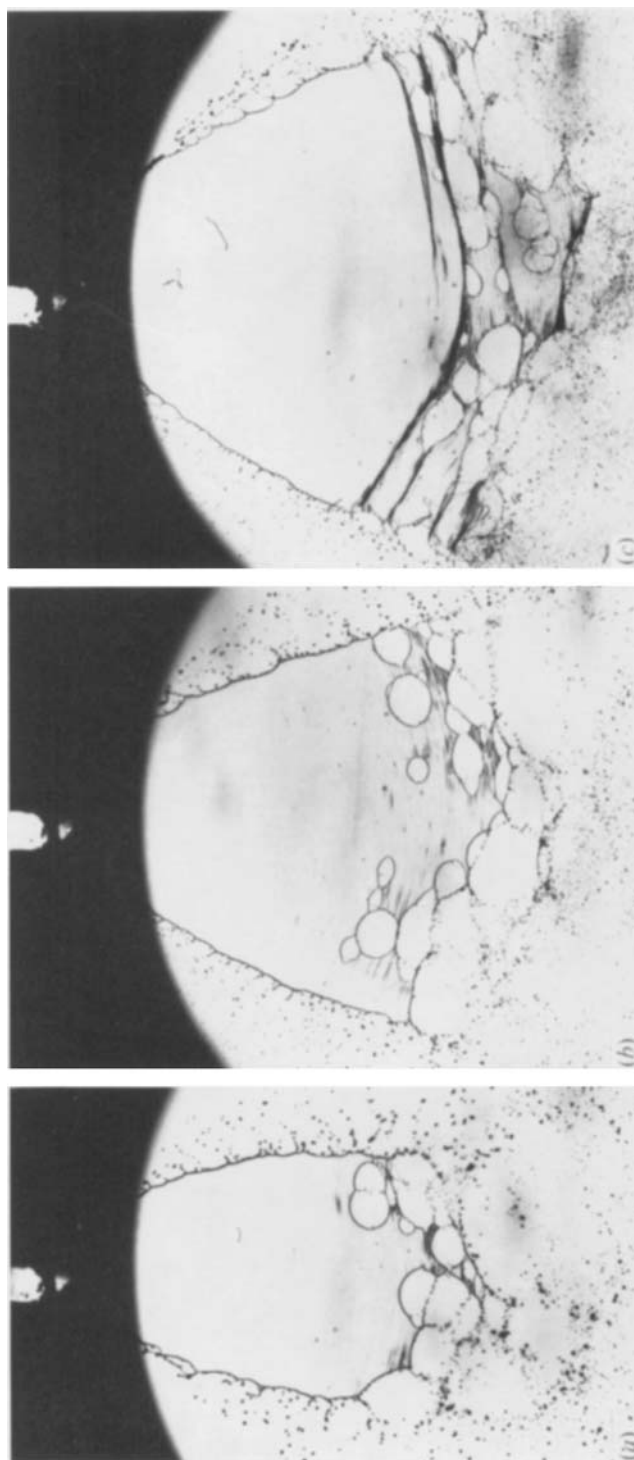


FIGURE 5. Wave formation on flat water sheets at a gas temperature of 675 °C (liquid temperature 24–26 °C); magnification $\times 1.7$.
(a) 1.72 bar, (b) 3.58 bar, (c) 6.35 bar.

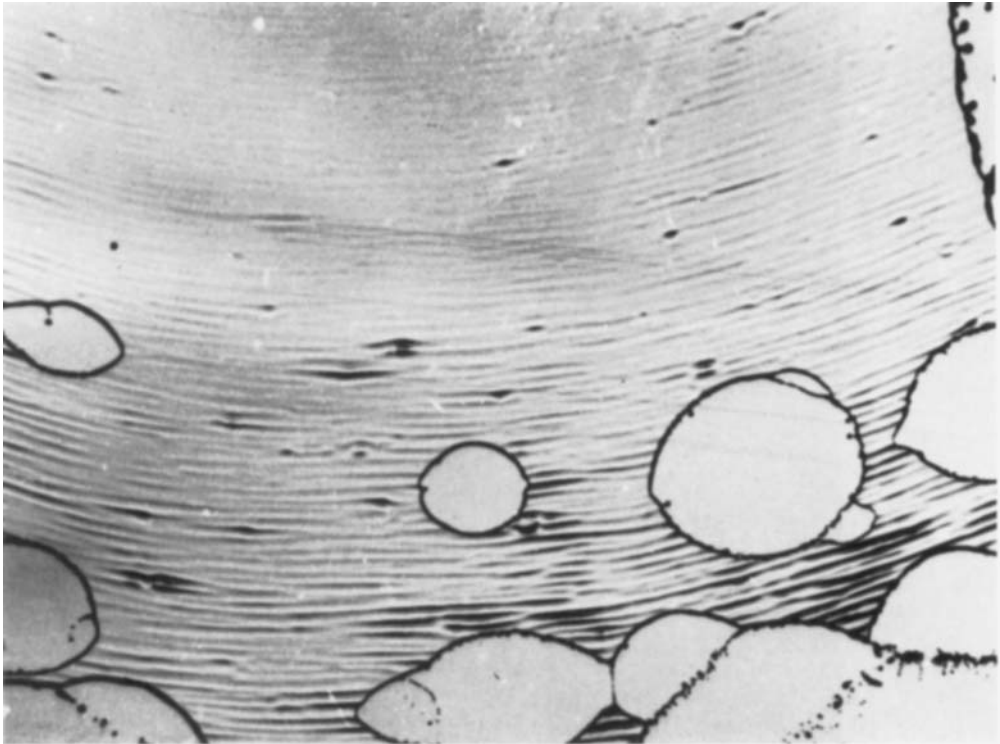


FIGURE 7. Region of disintegration at gas temperature of 675 °C
(liquid temperature 25 °C); magnification $\times 6.9$.

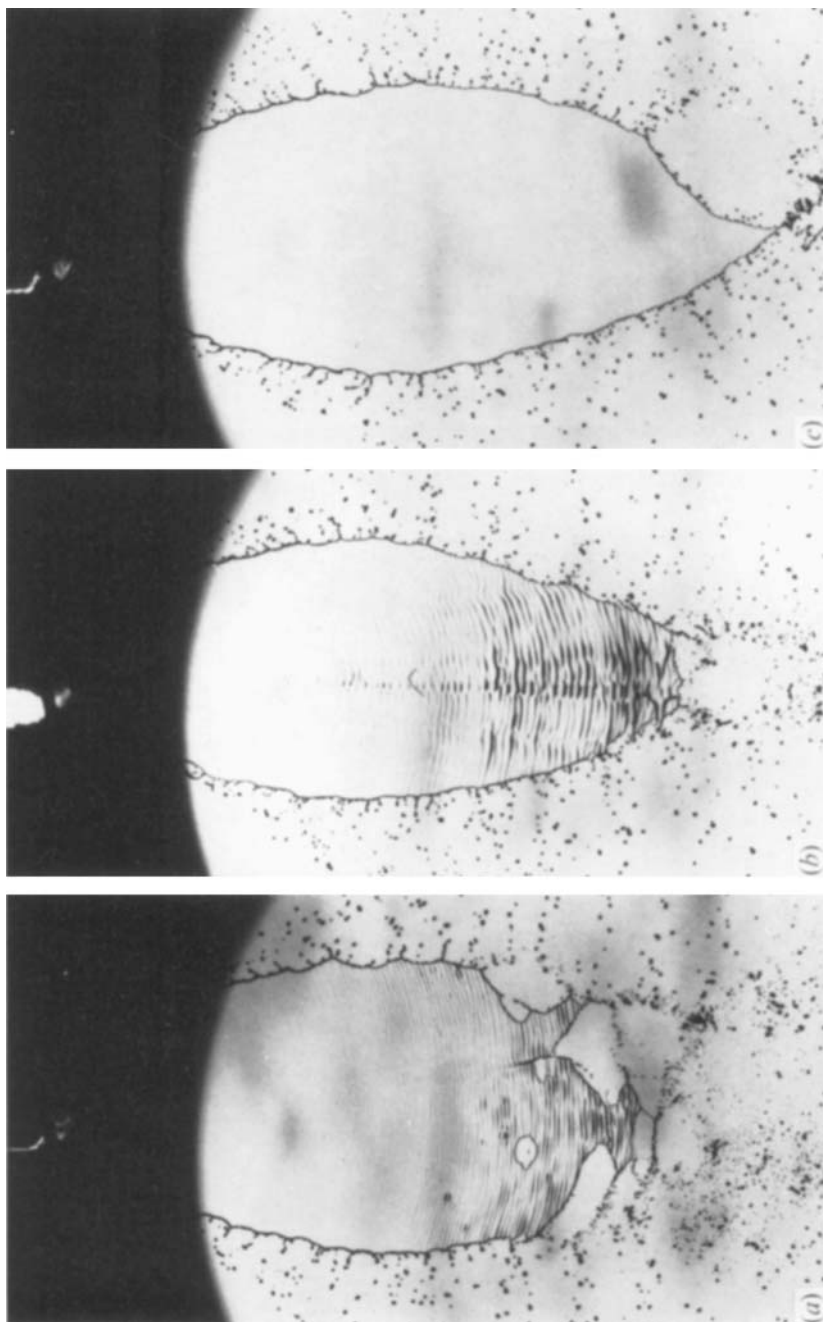


FIGURE 8. Photographs showing effect of liquid temperature on the mechanism of disintegration of flat water sheets at a gas temperature of 940°C ; magnification $\times 2$. (a) 1.72 bar, liquid temperature 56°C . (b) 1.59 bar, 67°C . (c) 1.72 bar, 78°C .

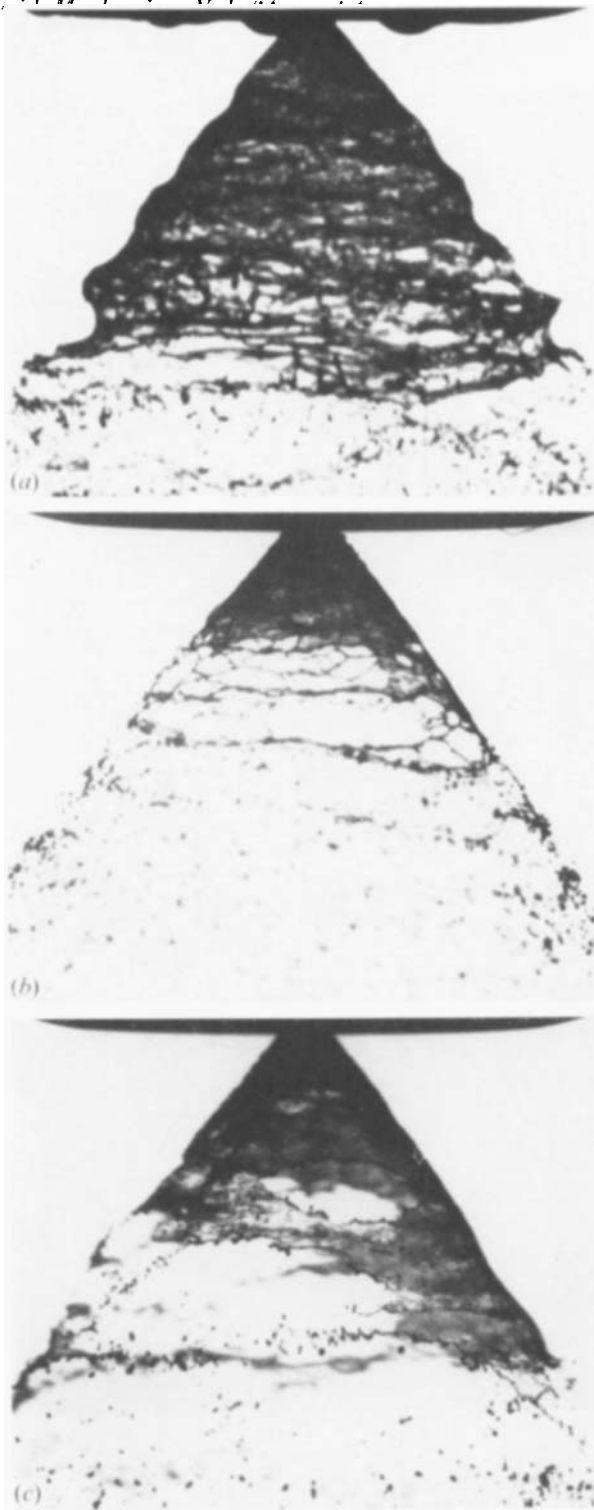


FIGURE 9. Photographs showing effect of both liquid and gas temperature on the mechanism of disintegration of conical water sheets (pressure 3.44 bar); magnification $\times 7.2$. (a) Gas temperature 20°C , liquid temperature 20°C , (b) 940°C , 26°C , (c) 940°C , 82°C .

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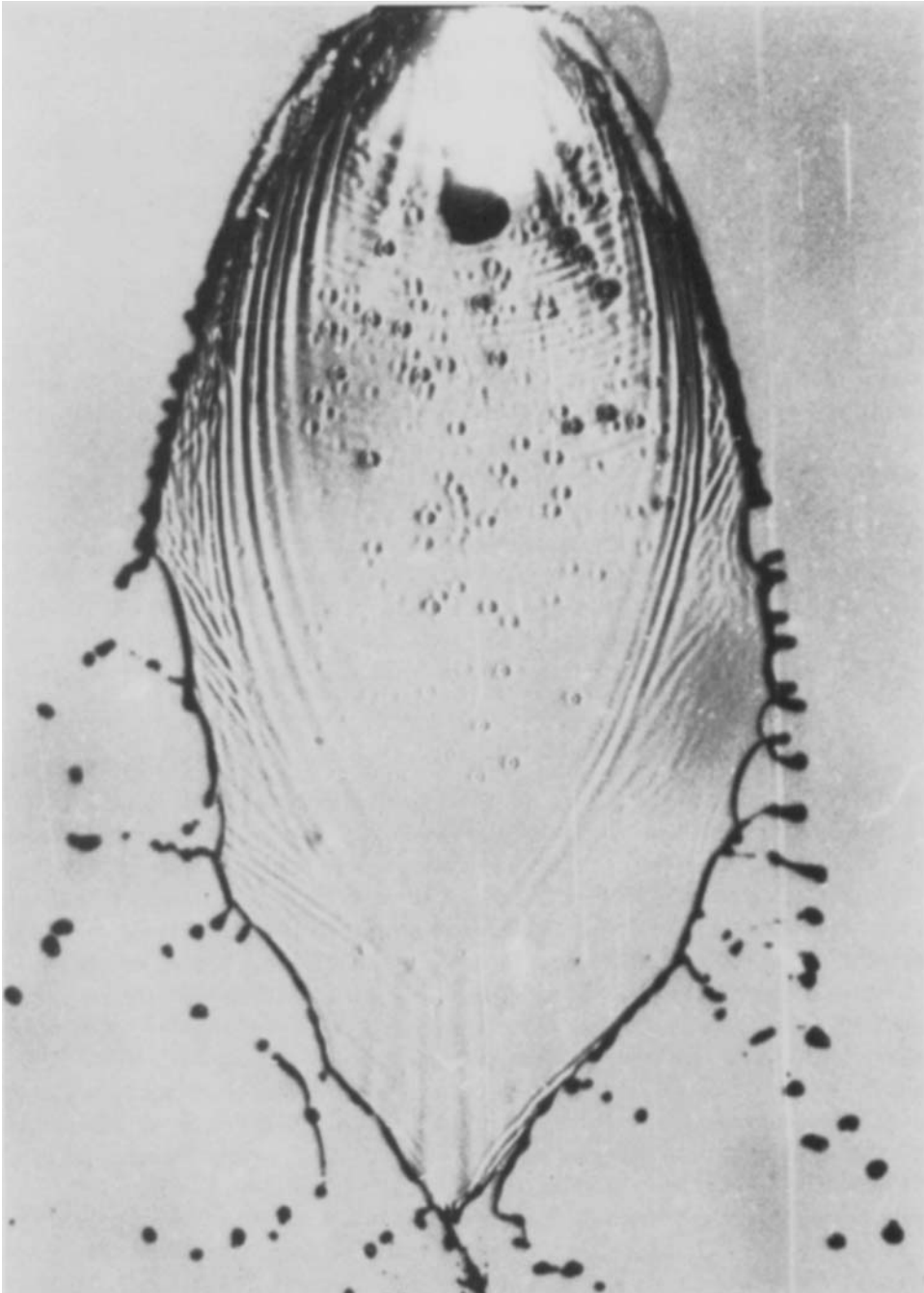


FIGURE 10. Appearance of flat water sheet formed at room temperature in presence of high frequency, high voltage spark discharge (injection pressure 0.69 bar); magnification $\times 5.8$.

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