GENERATION OF STATIC ELECTRICITY IN STEAM SCREENS AND WATER CURTAINS

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Static charge and field strength produced by steam jets and by a water atomiser have been measured; the effect on charging of design parameters in the systems has been determined. These results are discussed in relation to charging mechanism and to the production of incendive sparks.

INTRODUCTION

The recent development of processes in which water droplets are produced in close proximity to a flammable atmosphere has heightened interest in the static electrification of droplets. Accompanying this is the consideration of the probability of discharge of such a cloud of charged droplets to produce an incendive spark. Some aspects of the problem are new, but some have been examined over many years by cloud physicists as described in the 1971 Bakerian Lecture to the Royal Society (Mason(1972)).

In the more recent, interests considerations have centred around two main topics:

(a) A hazard is encountered in cleaning with water sprays or with steam jets, containers that have been used to store flammable and volatile materials. In both instances a cloud of charged droplets is produced and consideration must be given to the feasibility of producing incendive sparks at the time of discharge. This system is seen on a major scale in the explosions that have occurred in very large crude oil carriers. Amongst the possible sources of ignition discharge of static electricity seems to be the most likely.

(b) Water curtains and steam screens have been used in chemical plant to confine and to assist in the dispersion of vapour from spillages of highly volatile, flammable liquids. Again the possibility of producing an incendive spark must be considered. Similar factors could apply to spray cooling with water where a flammable atmosphere is present.

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In this paper the results of laboratory measurements of charge from steam jets and a water atomiser will be presented. Impact of such streams on stationary objects and the resultant dispersions have not been considered(vid.Vos(1971)). This work was commenced with four main questions in mind:

1. What is the magnitude of charges on droplets generated from both water and steam jets?
2. What factors influence these values?
3. How are the charges generated?
4. By what methods can incendive sparks be produced from clouds of droplets?

Contributions to answers to these questions will be presented; a more complete understanding depends on the results of further research.

PREVIOUS INVESTIGATIONS

As early as 1842 the discharge of static electricity from a jet of wet steam was recorded as capable of producing sparks 0.6m in length(Armstrong(1842,1843)). Measurements made in water sprays(Lenard(1892)) showed that the smaller droplets were negatively charged. Both in this work and in that of others (Frumkin(1924),Alty(1924)) reference was made to an electronic double layer at the air-water interface consisting of aligned dipoles with the negative polarity nearer to the interface. In earlier work(Simpson(1909)) it had been shown that shattering of large droplets(8mm in diameter) produced positive fragments surrounded by negatively charged mist. It was further shown that the average charge on distilled water droplets was 1.8×10^{-12}C. The breakup of falling droplets has been shown(Mason(1972)) to involve flattening followed by the formation of a rapidly expanding bag linked to an annular ring containing the bulk of the fluid. The bag in bursting produced fine spray in which the droplets carried an average charge of 3×10^{-12}C.

When salts were dissolved in water,the sign of the net charge in spray changed at high concentration and the value was specific for each salt(Lenard(1915));it depended on the degree of dispersion of the solution; the charge was higher for smaller droplets. The effect of dissolved salts was attributed to the inclusion of their cations in the double layer.

Droplets in the size range 80 - 150μm produced from bursting bubbles formed at a submerged air jet,were negatively charged for distilled water and for solutions of ammonium sulphate,sodium nitrate and carbon dioxide at less than 10^{-4}M and at a slightly higher concentration for smaller droplets(Iribarne and Mason(1967)) Average charge per droplet ranged widely from 3.3×10^{-14}(-ve) C to 3.3×10^{-15}(+ve). When various additions were made to 0.1M potassium chloride,n-propanol was found to reverse the sign of the charge and increase it tenfold(Iribarne et al (1970)).

When a jet of a dilute aqueous solution of sodium nitrate impinged on a metal sphere,it was found that charging was proportional to the square of the conductivity(Vos(1971)). Charge on fine mist produced from demineralised water was (-ve)1.7×10^{-6} Cm^{-3}. When surfactants were added to the water the sign of the charge on the droplets was the same as that of the surface active ion; a maximum value of charge was observed at a given velocity. Again fine mist was always negatively charged,but the total charge on the mist was positive over the range of concentration 10^{-3} to 10^{-1}M, but became negative for 1M solutions.

EXPERIMENTAL

Steam jet

A steam supply at pressures up to 70 kNm^{-2} was metered to a nozzle orientated to produce a vertical steam plume. Nozzles of two sizes were used and were produced by drilling a 1.5mm and a 3mm hole in separate pieces of brass tubing. A chromel-alumel thermocouple was mounted in the tube to monitor the quality of the steam supply. Charge was measured by placing probes in the steam plume and connecting these to a Keithley 610C electrometer(range 10^{-14} to 10^{-3}A). The probes were made of copper and were differently shaped - cylindrical,triangular,square - but they had the same projected area relative to the flow in the plume.

Measurements of field strength were made using a Davenport Field Meter mounted 0.7m or more from the axis of the jet. The applicability of this technique was limited by condensation and splashes on the head of the instrument.

Further experiments were undertaken using a steam supply at up to 600 kNm^{-2}. As before a thermocouple was used to monitor the quality of the steam. With this steam supply a series of nozzles was used; these were fabricated from 6mm O.D. brass tubing of I.D. 1.5,3 and 5mm . A nozzle of stainless steel 3mm I.D. was also used. The nozzles of I.D. 3 and 6mm were also used at various lengths.

Water jet

No attempt was made to produce a water curtain in the laboratory. Jets of water were produced,but the amount of breakup was minimal and it would be expected that static electrification would be arising in the main from the streaming current generated in flow through the feedpipe. Attention was centred upon the droplets produced from the water curtain and an attempt to simulate this in the laboratory was made by using a compressed air-driven atomising nozzle. To facilitate examination of charging of water to which additions had been made,liquid was fed to the atomiser from a container pressurised with nitrogen. Consdierable practical difficulties were experienced in measuring charge. Several probes were tried; the most successful design was based upon a direct connection to screened cable which was covered in rubber tubing and had Teflon sheets placed at intervals along its length in order to minimise the risk of earthing the probe. It was found to be necessary to enclose the apparatus in order to retain the water and this had to be combined with adequate screening and ease of manipulation of measuring probes. These requirements were met by u sing a combination of polythene sheeting and aluminium foil.

Droplet size

In both experiments with steam and with water an estimate was made of the range of droplet sizes. For the steam,jet,slides coated with magnesium were exposed at various positions in the plume; these were subsequently examined under the microscope. For the water jet a mean droplet diameter was calculated using an appropriate empirical relation(Nukiyama and Tanasawa(1939)). The value calculated was 57μm.

RESULTS

Low Pressure Steam Jet

When low pressure steam was fed to a cold nozzle the current registered, varied considerably as shown in Fig.1. The value became more strongly negative when water droplets were emitted. Probes of different sizes and shapes were placed in these plumes and the currents recorded were in the range (-ve)0.1 to 10 x 10^{-8}Acm^{-2}. These are illustrated in Fig. 2 where it will be noted that the charge collected produced an increasingly large negative current as the height of the probe in the plume increased. This effect is shown more clearly in Table 1 where the reults are expressed as charge per gramme of steam fed to the 1.5mm nozzle. In view of the fact that the amount of steam colliding with the probe will decrease as dilution increases at greater heights in the plume, these values give a more meaningful indication of charge producee. Further it will be noted that the value of charge collected depends on the type of probe used .

TABLE 1 Variation of Charge per Gramme of Steam in a Low Pressure Plume generated from a 1.5mmI.D. Brass Nozzle

Probe Height (m)		Charge per gramme of Steam ($C\ g^{-1} x\ 10^8$)		
	Probe type	SF	SC	LC
0.05		- 1.8	- 0.4	
0.10		- 20.8		- 3.4
0.20		- 87	- 23.2	- 3.4
0.30		- 282	- 116	- 160

SF Small flat probe; area 1.82 cm^2
SC Sma 11 curved probe; area - projected 1.62 cm^2
surface 3.99 cm^2
LC Large curved probe; area - projected 1.62 cm^2
surface 7.98 cm^2

These values were calculated, making the simplifying assumption that there was even distribution of steam across the section of the plume. A more detailed approach based on the droplet sizing technique gave results shown in Table 2. The increase of negative charge with height is again apparent. The values of field strength can only be taken for purposes of comparison. The appropriate estimates of drop size are shown in Table 3.

The variation of charge per gramme of steam fed to stainless steel nozzles of I.D. 1.5 and 3mm is shown in Fig.3. Charged dropletswere collected by impaction on a cylindrical probe and the values increased with increasing height. The current measured with cylindrical probes was, under some conditions, as small as 10% of that measures with flat square or triangular probes of equal projected area. However these results still suggest that there is an effect due to the material from which the nozzle was fabricated.

TABLE 2-Charge per Gramme of Steam and Field Strength at 1.5 and 3mm I.D. nozzles

Probe Height (m)	Charge per grame of steam ($C\ g^{-1} \times 10^{8}$)		Field Strength (Vm^{-1})	
Nozzle I.D.	1.5mm	3mm	1.5mm	3mm
0.05	- 3.5	+ 0.26	30	20
0.10	- 18	- 4.4	-15	10
0.15	- 100	- 9.1	-15	15
0.30	- 700	- 50	-30	30
0.50	- 1000	- 146	-25	-50

TABLE 3 - Estimates of Droplet Size at 1.5 and 3mm I.D. nozzles

Height of Collection (m)	1.5mm I.D. Nozzle No. of drops mm^{-1}	Size (m) Low	Size (m) High	3mm I.D. Nozzle No. of drops mm^{-1}	Size (m) Low	Size (m) High
0.05	18	40	70	10	85	250
0.20	13	50	120	9	70	125
0.50	5	80	250	3	80	150

High Pressure Steam Jet

When steam at higher pressures was fed to a nozzle, it was more convenient to mount the axis of the nozzle in a horizontal direction. Total amounts of charge were larger and field strengths were greater than for the low pressure jets; currents registered by the probes were of similar order. The net charge close to the nozzle was negative and as shown in Fig.4 for a 1.5mm I.D. nozzle supplied with steam at 550 kNm^{-2} and changed sign at 0.08m from the nozzle. The height at which this reversal occurred decreased with increasing nozzle diameter, so that for the 1.25cm nozzle it was very difficult to detect. The value very close to the nozzle was $- 2.6 \times 10^{-8}$A for the 1.25cm I.D. compared with $- 30 \times 10^{-8}$A for the 1.5mm I.D. nozzle for similar rates of steam flow.

Another difference from the experiments with low pressure (very wet) steam was that the time taken to establish steady values at pressures of 350 to 700 kNm^{-2} was between 5 and 10s while that for the low pressure system was up to 30min.

Field strength measured at 0.70m from the steam plume increased downstream of the nozzle and increased with increasing steam pressure. Clearly after a certain distance,the value of which depends on steam pressure and nozzle diameter, the field strength willfalloff. The values given in Table 4 are illustrative of this behaviour; they relate to a 3mm I.D. stainless steel nozzle fed with steam at 70,105,200 and 380 kNm^{-2}.

The results of investigating another parameter in the system are shown in Fig.5. The 3 nozzles used were all of 6mm I.D.,but the values of the L/D ratio were 0.8,1.6 and 14.4 i.e. lengths of 5,10 and 85mm. A significant increase in field strength was noted as L/D increased; field strength was measured at 0.70m from the plume or was converted to that basis.

TABLE 4 - Variation of Field Strength with Distance from a 3mm I.D. Nozzle for a Range of Steam Pressures

Distance from Nozzle (m)		Field Strength ($kV\ m^{-1}$)			
	Pressure	70	105	200	380 kNm^{-2}
0.15		0.5	0.65	0.9	1.5
0.30		0.6	1.0	1.35	3.3
0.70		0.85	1.45	1.8	4.2
1.0		1.0	2.0	2.4	5.4
1.5		1.35	2.7	2.7	6.0
2.0		1.2	2.4	2.4	6.0

Nozzles of both brass and stainless steel were used and while results from both have been quoted above, no direct comparison is possible. In Fig.6 values of field strength are shown for nozzles of similar dimensions operated uuder the same conditions. The field strength using the brass nozzle was approximately double that for stainless steel. Values of currents drawn from the probes were higher for the brass nozzles as shown in Table 5.

TABLE 5 - Currents drawn from Probes placed in Steam Plumes formed at 3mm I.D. Stainless Steel and Brass Nozzles

Distance along plume (m)	Brass ($A \times 10^8$)	Stainless Steel
0.05	- 4.5	- 11.3
0.30	2.25	0.2
1.0	2.5	0.22

Water Atomiser

Experiments were undertaken in which the following were fed to the atomiser at a range of rates and air supplies:
tap water, 10^{-3} and 10^{-1}M sodium chloride, tap water containing ca. 250 cc m^{-3} of Teepol.

In Fig.7 the variation of charge with height of probe above the atomiser is shown for two air flowrates at a constant water supply to the atomiser. The peak value of charge registered was equivalent to - 5.5 x 10^{-10}A. There was evidence of positive charges in that the electrometer occasionally registered these at values 10 to 15 times greater. The lateral distribution of charge in the plume is shown in Fig .8 for water flowrates of 230 and 355 cc s^{-1} and air flowrates of1500 and 2500 cc min^{-1}.

In summary these experiments showed that:
1. Charge increased with greater air input i.e. greater atomisation, for a given feedrate of water
2. The height at which maximum current could be drawn from the probe increased with greater feedrate of water
3. The highest current recorded was - 5.5 x 10^{-10}A at ca.0.30m above the atomiser with 290cc s^{-1} of water and 0.02 $m^3 min^{-1}$ of air.

When solutions of sodium chloride were supplied to the atomiser,the current measured close to it was negative,but that at greater heights was positive. The measured values are shown in Fig.9 where the effect of concentration of sodium chloride is also shown; both negative and positive currents were greater for the 10^{-1}M than for the 10^{-3}M solution.

Also shown in Fig.9 are the reults with the solution of Teepol; positive charges were produced at all the heights at which measurements were taken. The maximum current was roughly double that for 10^{-1}M sodium chloride and was of opposite sign; it was about 100 times greater than the value for tap water.

DISCUSSION

The results set out above offer information on the size and sign of charges generated in steam plumes and water mists. From these it is possible to gain some insight into the likely results from steam screens and water curtains. When steam is introduced into a cold pipe, condensation will occur. If the steam continues to flow, the pipe will warm up and condensate will be expelled from the nozzle. There are then several processes to be considered relating to static charging in this system. These will be dependent on charge separation at the double layer at the interface (Gouy (1910)).

Some droplets suspended in the steam may collide with the pipe wall and charge separation willoccur. Considerable quantities of water will move over the inner surface of the pipe; charge separation will take place leaving a net charge on the fluid. This charge will relax according to the value of τ

where $$\tau = \frac{\varepsilon\varepsilon_0}{\kappa}$$

For aqueous solutions ε = ca.80, but κ varied over a wide range in the work reported above (1×10^{-4} to 1×10^{-1} Sm^{-1} i.e. τ will vary from ca. 7×10^{-4} to 7×10^{-7} s). There is then a possibility of some electrification of the fluid, but it will disappear rapidly unless the charge becomes isolated as in a droplet. Thirdly, the film will move through the nozzle whereupon liquid threads may form, producing both positive and negative charges (Mason(1972)).

The steam plume then contains a mixture of water droplets and condensing steam vapour and the development of charging is as shown in Fig.1. Although the charge per unit weight of steam is greater than that from unit weight of atomised water, the surges indicated are short-lived and the instantaneous rate of flow of the water is high. The effect, therefore, is marked.

In the case of the water atomiser, water reaching it will be charged due to separation in flow through the feedpipe. Some values of streaming current are given in Table 6; they have been calculated from

$$i_s = -\tfrac{1}{2} f \, Re \, \bar{v} \, \pi \varepsilon\varepsilon_0 \zeta$$

These values are typical of the range of operation in this work, and are of the same order as those that could be deduced from the results taken ata height of $\tfrac{1}{2}$m and shown in Fig.7. However, this must be considered with several other results. The values shown in Fig.8 for probe currents taken at 0.3m indicate a lower net charge. The low values of relaxation time have already been noted. Further, separation of charged droplets by gravity will take place. It

TABLE 6 - Values of Streaming Current for a Range of Water Flowrates in a Pipe of I.D. 1.27×10^{-2}m

Flowrate ($m^3\ s^{-1} \times 10^6$)	$\bar{v} = Q/A$ ms^{-1}	Re	i_s $A \times 10^{-8}$
180	1.421	13784	0.8
238	1.879	18226	1.3
290	2.289	22208	1.9
355	2.802	27186	2.7
408	3.220	31244	3.4

seems probable that in the light of these considerations and that the water must pass through the atomiser after this charging process,the major charging process is that of rupture of liquid filaments(Mason(1972)). In the water curtain this will occur as spray forms at the edges and topmost extremity.

The methods used to measure both charge and field strength require some comment. Measurements made at a distance from the plume will be influenced by the whole plume,although mainly by the regions of the plume nearest to it. The probe is mainly influenced by droplets that rise to its height and those that would rise above it; increasing gravity separation will occur with height. There is, therefore, likely to be differences between values that may be deduced from the experimental results. The insertion of a probe in a plume with its connecting lead may cause both electrical and aerodynamic effects. As shown in Table 1 and Fig.2 the current generated varied with the shape of the probe; other experiments showed that its orientation is also of importance. Condensate dripping from the probes caused sudden and major changes in value e.g. a steady reading of (+ve) 0.8×10^{-7}A fell suddenly to (-ve) 0.8×10^{-7} A. This phenomenon has been observed and discussed previously (Makin et al(1970)).

The results given in Fig.6 show that the material of the nozzle has a significant effect upon both charge and field strength. Small effects,up to 7%,have been reported previously(Graydon and Goodfellow(1968)) using liquids of low conductivity. Insufficient is understood of the system to explain this change,but it may be noted that stainless steel is more cathodic than brass,is a poorer conductor of electricity and has a different work function.

A further aspect of the effect of the nozzle is shown in Fig.5. Increase in length of the nozzle produced an increase in field strength over the range of steam pressures examined. As L/D is altered,the flow through the nozzle will change both in composition and aerodynamically. Previous work(Luus et al(1963)) with a Teflon tube showed that constriction was capable of reversing the sign of the charge. Magnitude of the positive current was about ten times that of the negative

Size of Charges

Various workers have determined charge on single droplets,but in the present workefforts to do this were not warranted. Single drops produced by the breakup of 10µm threads of dilute aqueous solutions carried a charge of 3 fC(Mason(1972)) and for droplets from bursting bubbles,in the range 50 to 200 m dia.,the charge varied from (-ve)0.3 pC to (+ve)0.3 fC as both salts and dissolved carbon dioxide increased above $10^{-4}M$; charge passed through a minimum at this value(Iribarne and Mason(1967)).

Values obtained in the present work for charge on water mist was ca.2 x 10^{-6} Cm^{-3} which is in agreement with the value obtained by Vos(1971).

The amount of charge collected per unit area of probe in unit time varied with the composition of the liquid dispersed and the position in the plume. Some values are given in Table 7,and when account is taken of the widely differing experimental methods used the degree of agreement between various workers is substantial.

TABLE 7 - Comparison of the Amount of Charge collected per Unit Area of Probe in Unit Time

Liquid	Iribarne et al (1970)	Makin et al (1970)	Present Work
	(C per 100 mm^2 per second)		
Water	-1.7×10^{-9} to $+3.5 \times 10^{-10}$	-0.8×10^{-10}	-3.7×10^{-10}
Sea Water		$+0.25 \times 10^{-12}$	
Sea Water + Detergent		$+0.7 \times 10^{-12}$	
$10^{-1}M$ Na Cl			$+2 \times 10^{-10}$ to -2×10^{-10}
Teepol solution			$+4 \times 10^{-8}$

Charge in the steam plume expressed as coulombs per gramme has already been given and are summarised in Table 8. The shift towards higher positive values occurred as less water condensed in the feed pipe. The effect of the negatively charged water droplets became less when high pressure steam was used.

TABLE 8 - Charge generated in a Steam Plume formed at Stainless Steel and Brass Nozzles

Nozzle Material		Charge per gramme of steam fed to the nozzle ($C g^{-1}$)
Brass	Low pressure	-1000 to $+0.26 \times 10^{-8}$
	High pressure	-5 to $+ 326 \times 10^{-8}$
Stainless Steel	High pressure	$+ 280 \times 10^{-8}$

Incendivity of Discharges

In considering the possibility of an incendive spark being produced on discharge,account must be taken of both charge and field strength and of the nature of the discharge. Clearly the energy involved in the discharge of individual droplets is too small to produce an incendive spark. A number of mechanisms have been suggested whereby such sparks may be produced(van de Weerd(1973))

1. Accumulation of charges on insulated objects. This process is

unlikely to be dangerous where the charge carriers are of low mobility, but for highly charged steam mists there is evidence that incendive sparks may be produced.

2. Objects containing an induced charge; such objects are initially earthed and on severance from earth the object carries charge with it. This may discharge as a spark if the object returns to earth or as a corona discharge during its period of freedom.

3. Objects acquiring a nett induced charge that may be earthed in a strong field. A spark may result.

4 . Charges remaining on an object after earth contact. The geometry of the object may allow of the possibility of corona discharges.

Considerable attention has been paid to unbonded objects (3) which may be 'water slugs' (Hughes et al (1973) and van de Weerd (1973)) or metal objects fallimg through a field and subsequently being earthed. In the work cited it has been shown that in tank washing, corona discharges do not present an igniton hazard, but that spark energies resulting from falling objects are adequate for the ignition of hydrocarbons.

Estimates of the stored energy in steam plumes based on measures values of charge per gramme of steam, have been made and are given in Table 9. These estimates also depend on using 1 m^3 of steam as a basis of calculation and

$$E = \frac{\sigma a}{3\varepsilon_0}$$

No account has been taken here of the type of discharge that may result or of the rate of energy release, but these maximum values indicate that sufficient energy for ignition may be stored in relatively small volumes.

TABLE 9 - Estimates of Energy stored in 1 m^3 of Steam Plume

Nozzle Dia. (mm)	Steam Flow $g\ s^{-1}$	Charge (10^{-8}C g^{-1})	E (kV m^{-1})	W (mJ)
1.5	2.10	-6.2	20	0.6
3	2.20	-3.2	10.3	0.16
6	4.50	-1.4	4.5	0.03
12.5	18.00	+0.5	1.4	0.004

'Cloud-earth' discharges have been studied (Hughes et al (1973)), and it has been shown that they are of insufficient energy to produce an incendive spark.

The measurements reported above lead to the view that the hazard of water mists is likely to be less than that from steam plumes, but clearly there is evidence that uuder appropriate conditions they produce incendive sparks.

CONCLUSION

Brief reference will now be made to the questions set out in the Introduction. While at this stage of investigation complete answers cannot be offered, further relevent information has been obtained.

1. As suggested by the scatter of values obtained in other work (e.g. Iribarne and Mason (1967)) the size of the charge on individual droplets is probably of little importance. Values of charge per gramme of steam and per cubic metre of mist are more meaningful in assessment of the degree of hazard. The value of 2×10^{-6} C m^{-3} for water mist is in good agreement with that of Vos(1971). Values for steam, expressed in the units of C g^{-1}, ranged from $- 1000 \times 10^{-8}$ to 280×10^{-8}
2. Factors found to affect the amount of charge produced include:
    nozzle material
    composition (i) wetness of steam
    (ii) addatives to water
    rate of supply of either steam or water to the nozzle or atomiser, which in turn affects plume height, volume of mist and droplet size.
3. Charge generation depends on the L/D ratio of the steam nozzle suggesting that the streaming current makes a significant contribution when wet steam is used. The water experiments bear out the idea that charge is generated from the breakup of liquid filaments probably involving the separation of dipoles.
4. Charge accumulating on insulated conductors such as metal work and 'water slugs' is sufficient to produce incendive sparks on earthing.

These partial answers lead to the conclusion that a hazard exists with both water curtains and steam screens. The hazard can be minimised and is less likely to be realised with water curtains than with steam screens, but this will depend on the detail of the particular system. The balance of advantage against degree of hazard with these systems and the probability of ignition when sufficient energy is stored in the system are both questions that require further investigation.

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REFERENCES

Alty, T., 1924, Proc.Roy Soc., A106, 316

Armstrong, W.G., 1842, Phil. Mag., 20, 3
1842, Phil. Mag., 22, 1
1843, Phil. Mag., 23, 194

Frumkin, A., 1924, Z.phys.Chem., 109, 34

Gouy, P.M., 1910, J.Phys., 9, 457

Graydon, W.P., and Goodfellow, H.D., 1968, Can.J.Chem.Eng.,46,342

Hughes, J.F., Bright, A.W., Makin, B., and Parker, I.F., 1973, J.Phys.D: Appl. Phys., 6, 966

Iribarne, J.V., Klemes, M., and Yip, C.L., 1970, J.Electroanalyt. Chem., 24, App.11 - 16

Iribarne, J.V., and Mason, B.J., 1967, Trans.Far.Soc., 63, 2234

Lenard, P., 1892, Ann.Phys., 46, 584

Lenard, P., 1915, Ann.Phys., 47, 463

Luus, R., May, Z., and Goodfellow, H.D., 1963, Can.J.Chem.Eng., 41, 167

Makin, B., Erin, T., and Bright, A.W., Proc.1st.Internat.Conf.on Static Electricity, Vienna, 1970, 459

Mason, B.J.,1972, Proc.Roy.Soc., A307, 433

Nukiyama and Tanasawa, 1939, Trans.Soc.Mech.Eng.(Japan), 5, 18

Simpson, G.C., 1909, Phil.Trans.Roy.Soc., A209, 319

van de Weerd, J.M., 1973, Proc.2nd.Internat.Conf.on Static Electricity, Frankfurt (in the press)

Vos, B., 1971, Static Electrification, Paper 15(iv), 184 ,(Inst. of Physics)

SYMBOLS USED

τ = relaxation time

ε = relative permittivity

ε_0= permittivity of free space

κ = conductivity

i_s = streaming current

f = Fanning friction factor =

τ_{so} = shear stress of liquid at pipe wall

$\bar{v}$ = mean velocity of liquid

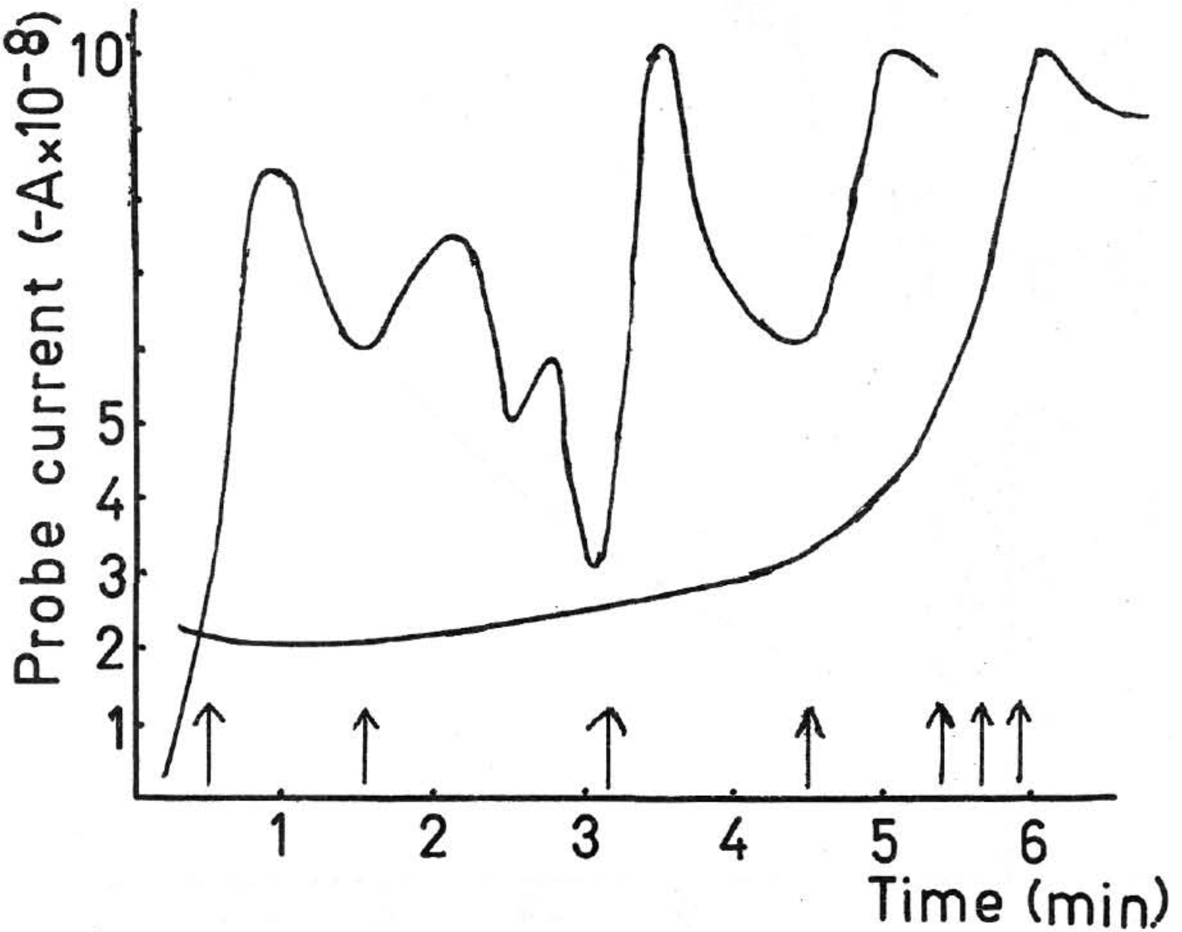
ρ = density of liquid

ζ = zeta potential

Re = Reynolds Number

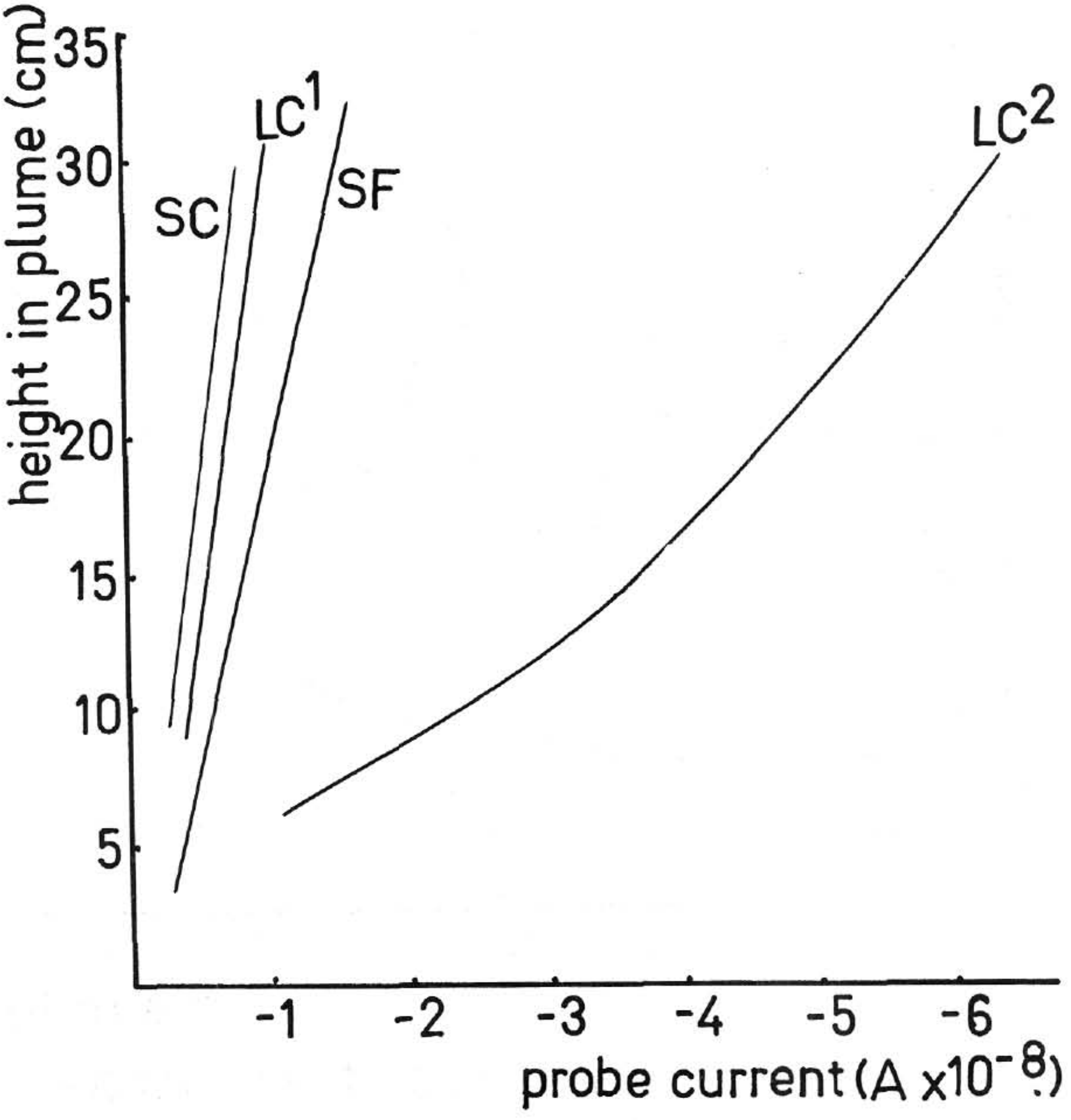
σ = charge density

a = radius of charged volume



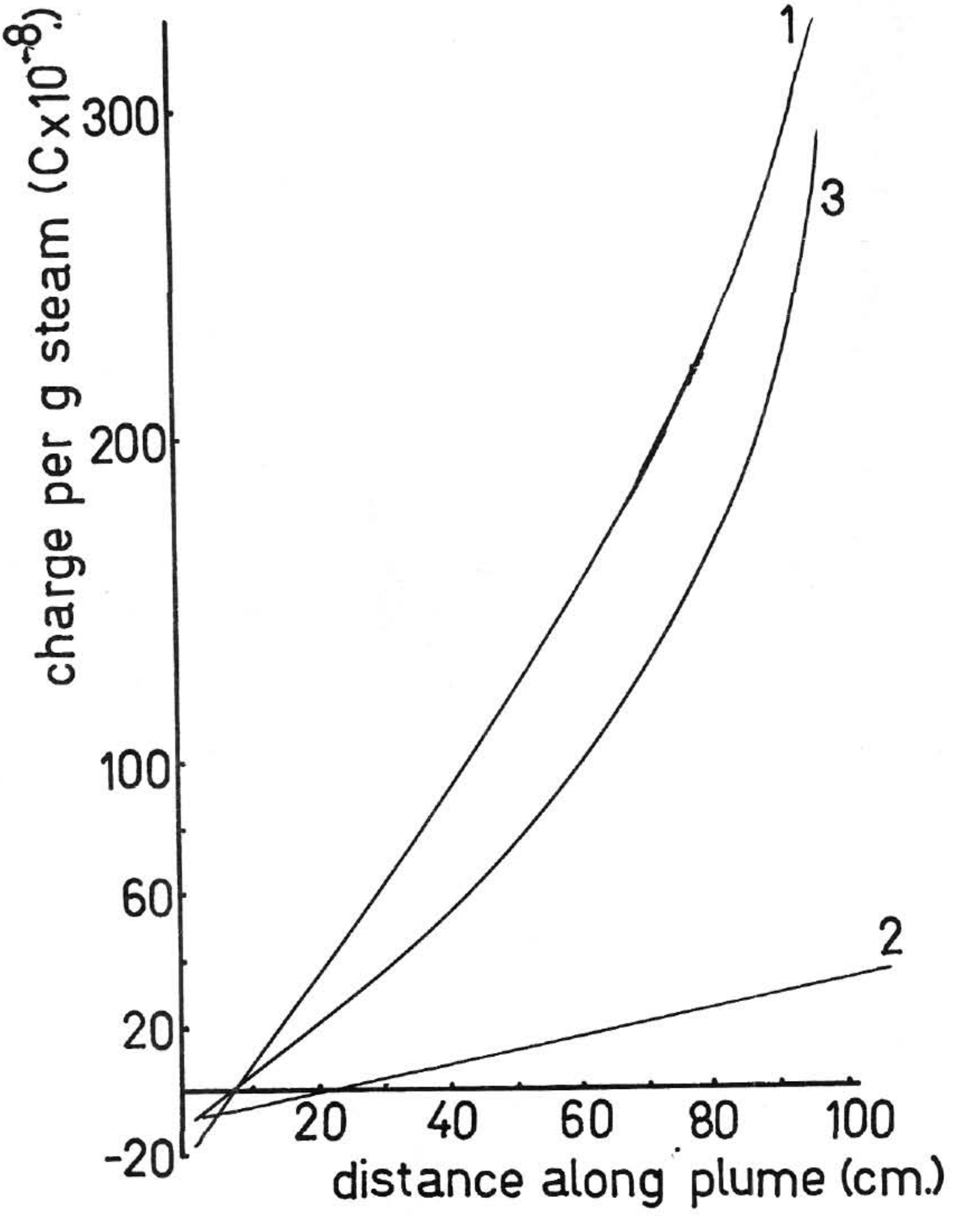
↑ emission of water spray from nozzle.

Fig.1: Graph of probe current vs. time.



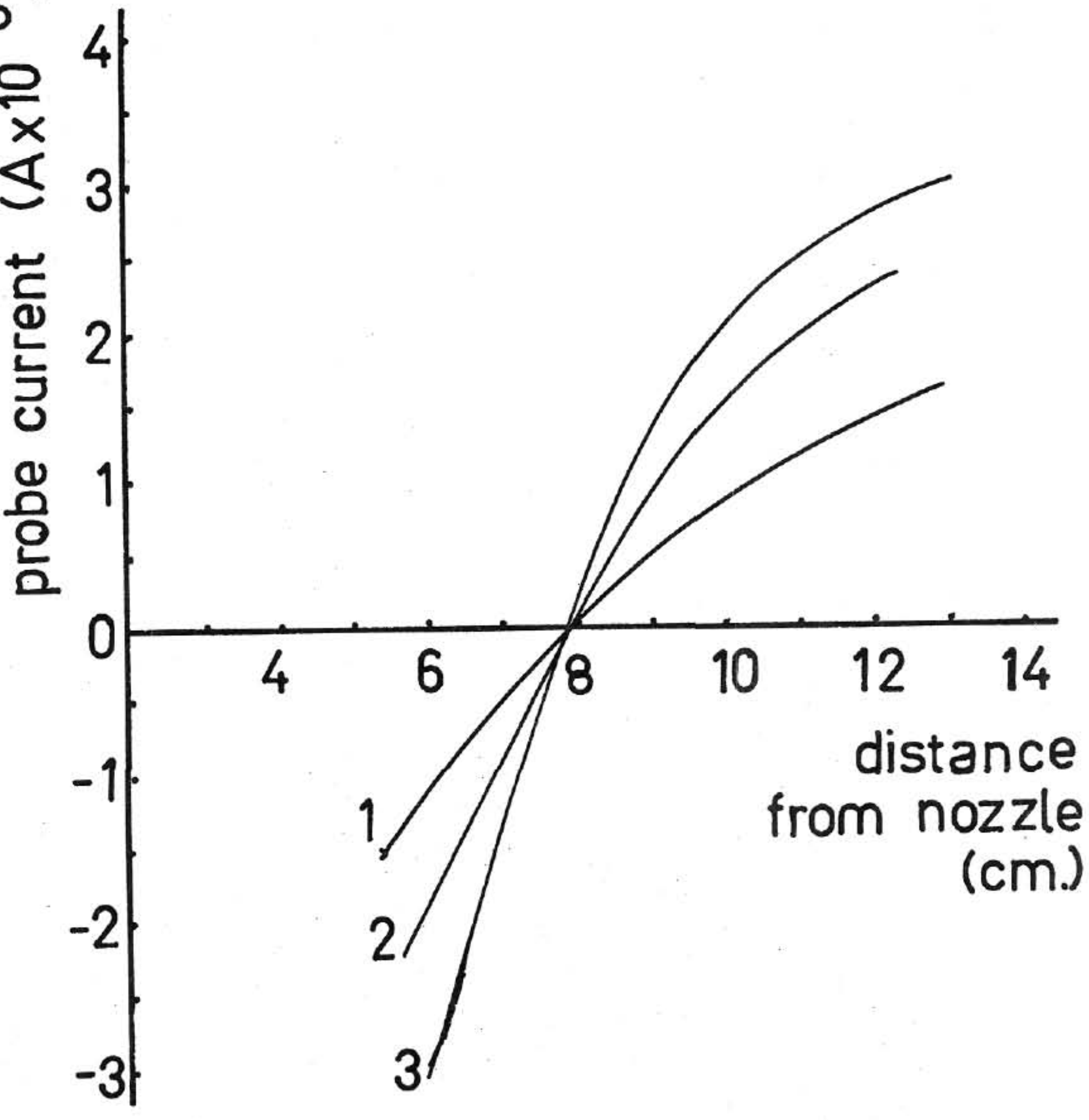
probes: LC^1 = large curved (+ preheat).
LC^2 = large curved (no preheat).
SF = small flat.
SC = small curved.

Fig. 2: Graph of probe current vs. height in plume.



nozzles: 1 = 3mm brass.
2 = 3mm stainless steel.
3 = 6mm " " .

Fig.3: Graph of charge/g steam vs. distance along plume.



probes: 1 = cylindrical.
2 = square.
3 = triangular.

Fig. 4: Graph of probe current vs. distance from nozzle.

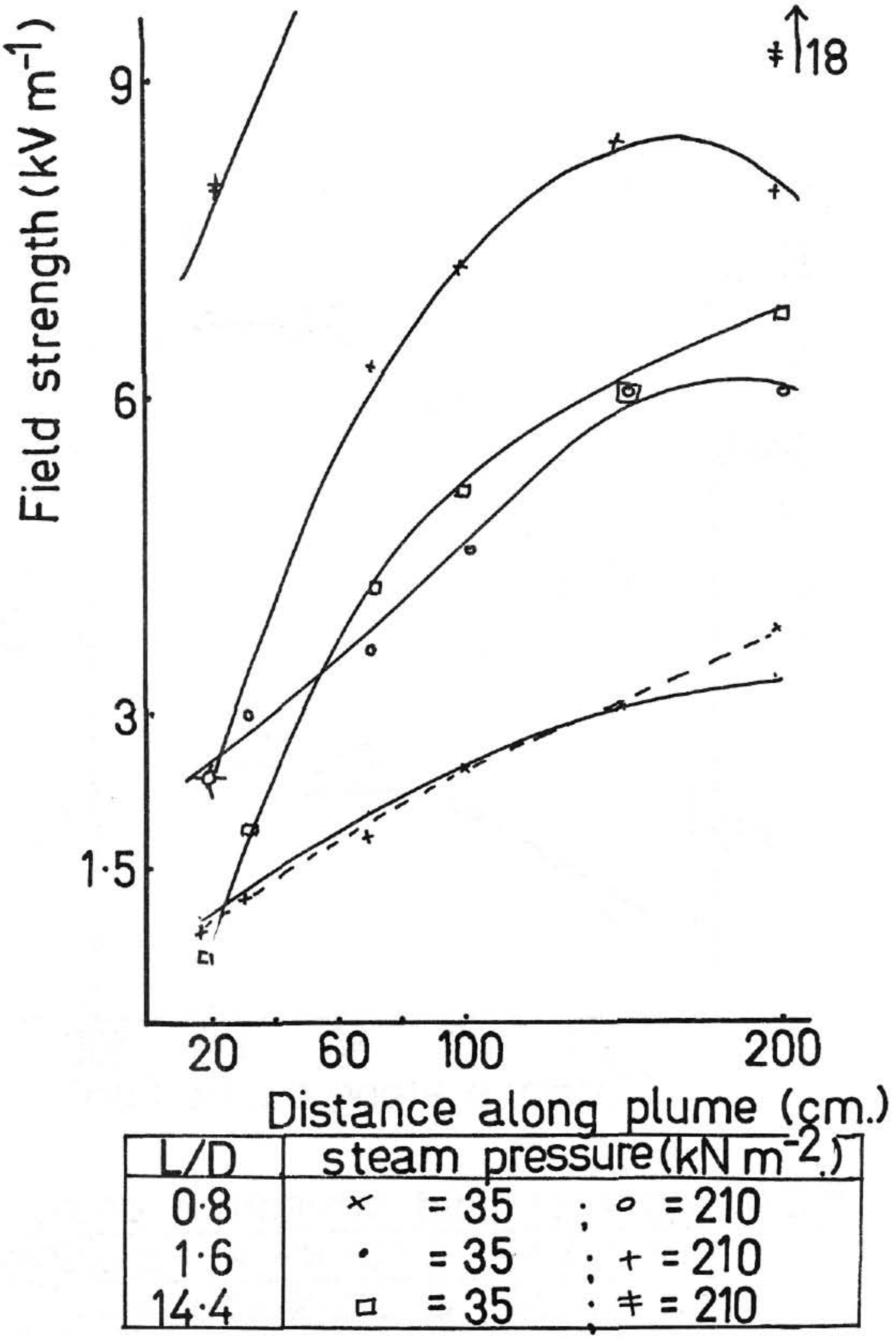


Fig.5: Graph of field strength vs. distance along plume

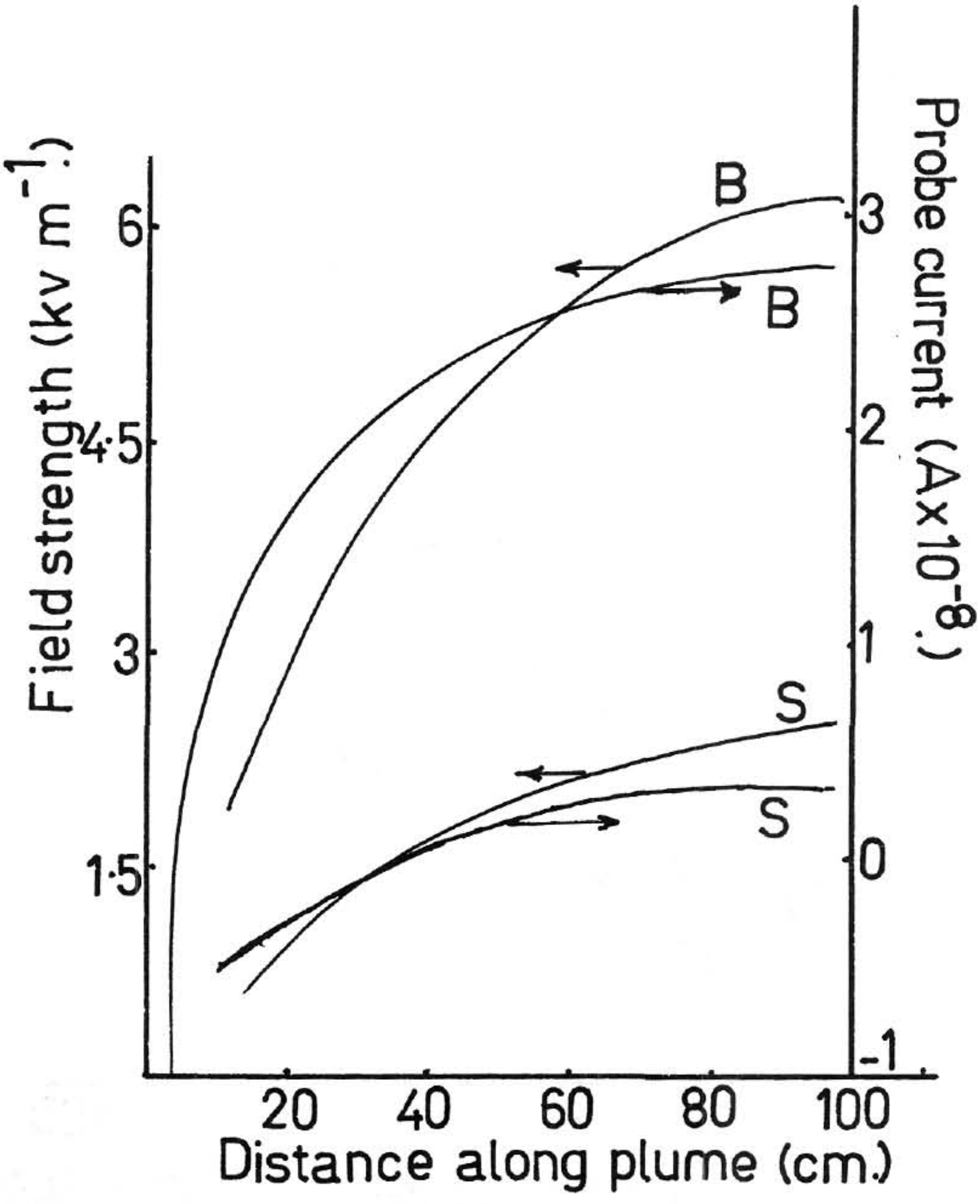
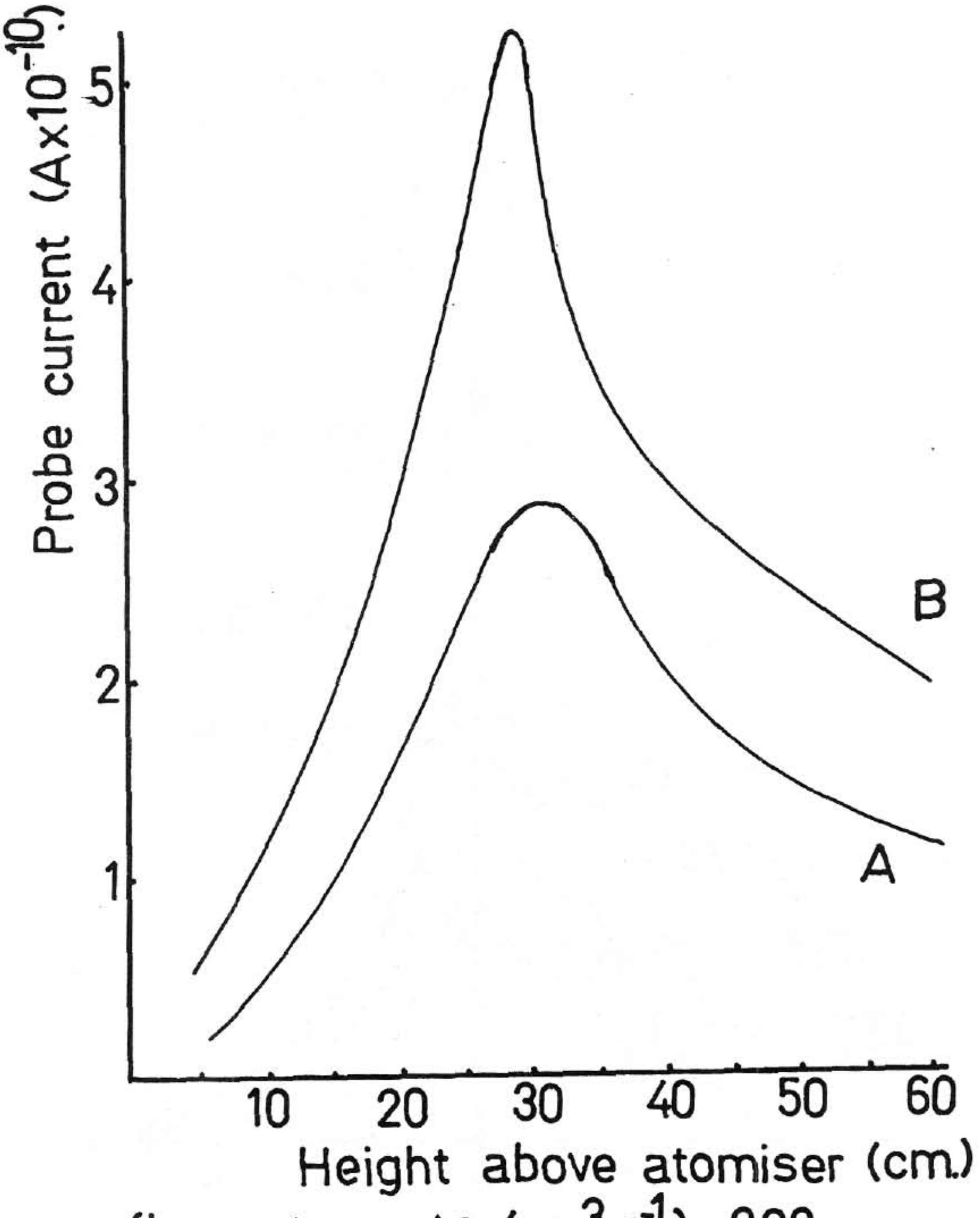


Fig. 6: Graph of field strength & probe current vs. distance along plume for brass (B) & stainless steel (S) nozzles.



flow rates:water(cm^3 s^{-1}), 292.
air(m^{3}min^{-1}), 0·01(A).
0·02(B).

Fig.7: Graph of probe current vs. height above atomiser.

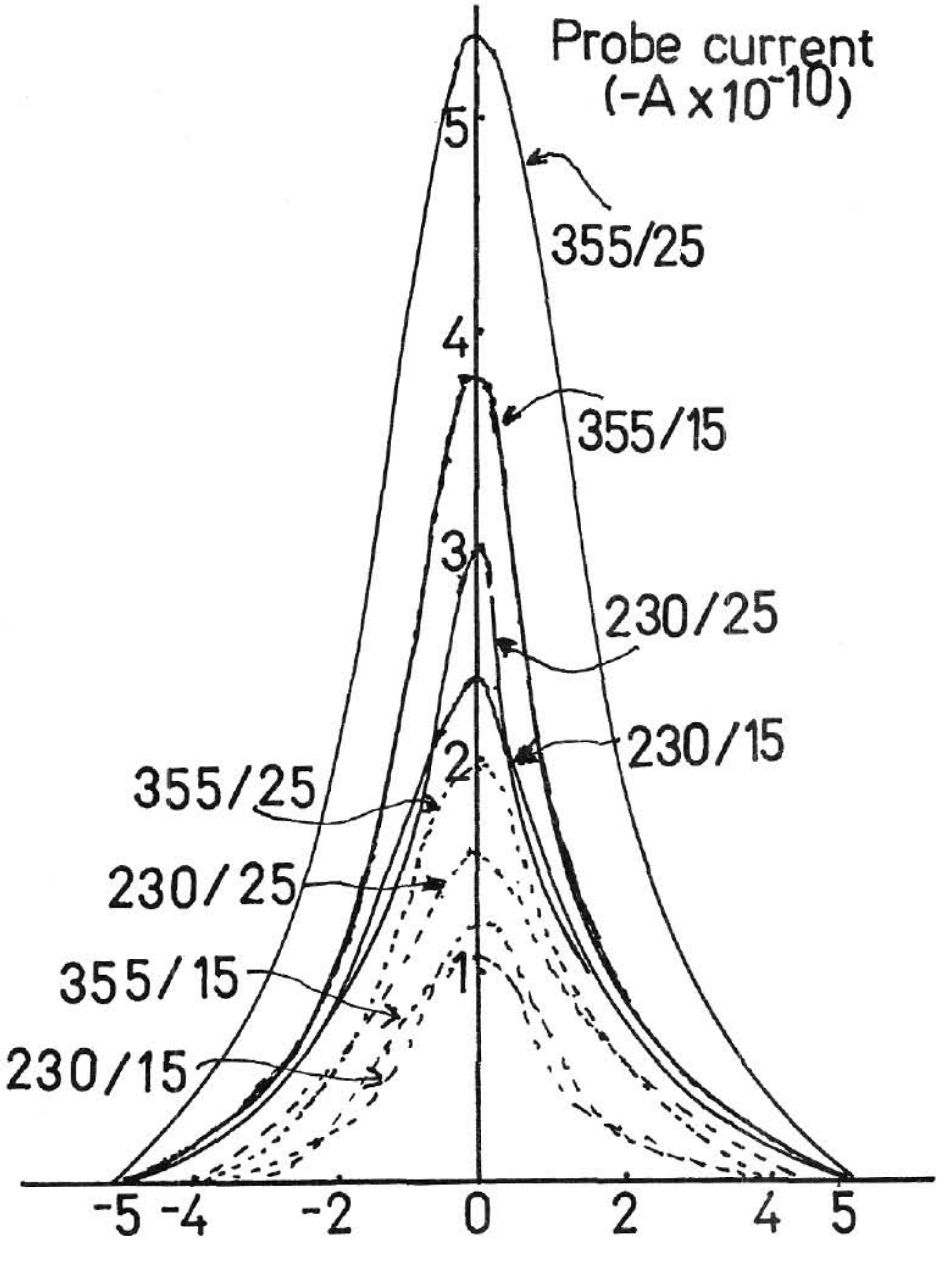
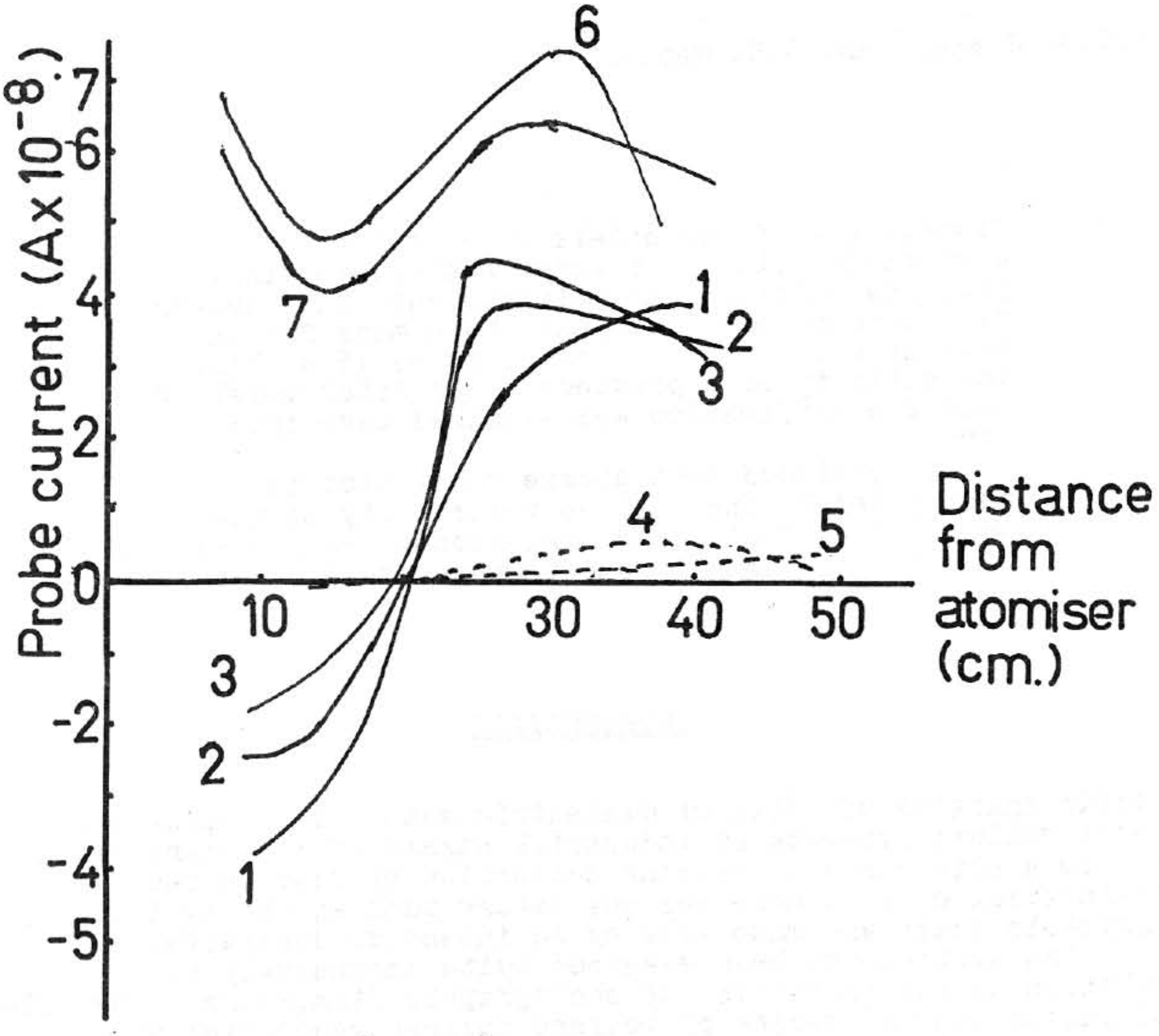


Fig.8: Graph of probe current vs. distance from atomiser ℄.



air rate ($m^3 min^{-1}$): 0·025
liquid rate($cm^3 s^{-1}$): 10^{-1}M. NaCl: 175 (1), 292 (2), 425(3).
10^{-3}M. NaCl: 425(4), 292(5).
Teepol : 425(6), 292(7).

Fig.9: Graph of probe current vs. distance from atomiser.