An Investigation of Electrostatic Phenomena Associated with Flowing Wet Steam with Particular Reference to the Wet Steam Turbine

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A wet steam tunnel was constructed to simulate the interaction of liquid and vapour in order to investigate the nature and origin of static electrification phenomena which occur within wet steam turbines. The tunnel was operated at 0·17 bar pressure with steam velocity up to 290 m/s.

The mechanisms likely to cause charging were investigated in turn. The major charging mechanism is 'separation charging' which occurs when a mass of water is torn rapidly from a solid surface. The rate of charging depends on the speed of separation, the geometry, and the surface contamination of the solid.

1 INTRODUCTION

It is well known that electrostatic phenomena are associated with flowing wet steam. Damage can be caused to rotor bearings and auxiliary drive gears by spark discharges and steam turbine designers have long found it necessary to provide earthing for rotors operating in wet steam. To the authors' knowledge there have only been three papers of significance (**1**, **2**, **3**) treating this subject. By contrast, the general subject of electrostatic charging associated with boilers, droplet fracture, fluids in motion, etc, has a long history of investigation and the reader is referred to Loftus (**4**) for further details.

In 1936, Sauer (**1**) investigated the electric charges produced by steam on turbine rotors and concluded that the cause was probably the 'Lenard Effect' (see later). He stated that (a) the sign of the charge and partly also its magnitude depends on the steam conditions in the last stages of the turbine and therefore also on the condenser vacuum, (b) at constant or near-constant vacuum the magnitude of the charge depends on the wetness in the last stages of the turbine and on the turbine load (and hence steam quantity). Sauer believed that the presence of a positive potential on a turbine shaft is indicative of active blade erosion.

In 1959, Gruber and Hansen (**2**) reported laboratory and field trials on turbines and discussed the several types of voltage found on the shaft, among which they listed an electrostatically-generated d.c. voltage. This type of charge was found only on condensing sets, but not on all condensing sets. They found difficulty in obtaining repeatable results, but affirmed that (a) the polarity of the shaft was generally, but not invariably, positive, (b) a high rate of charge generation occurred producing currents of 500–1000 μA, (c) discharge by sparking through bearing oil films to the journal caused pitting and eventual breakdown of the bearing surface.

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The most recent observations on charged droplets within the turbine were made by Thorpe and Wood (**3**) in 1969. They introduced into the LP end of a working turbine an electrostatic probe consisting of a charged wire the capacitance of which would be altered by droplet impact. It was anticipated that drop size could be inferred from measurements of the induced voltage pulse. However, it was found that pulses were registered in the absence of an applied voltage on the probe, which indicated the existence of charges on the collected droplets themselves. In 1950, one of the present authors (**5**) observed the same effect using an electrometer and collecting sphere in a steam nozzle apparatus discharging wet steam.

It is evident from references (**1**) and (**2**) that investigations on a turbine in service present grave difficulties and it was believed that the mechanisms responsible for the origin of the charges could be more profitably investigated by employing a wet steam tunnel in which individual events which might promote charging could be investigated in isolation. The following physical processes were considered as possible sources of charge separation:

(1) Evaporation and condensation,
(2) Relative velocity of phases at their mutual interface, or at a boundary,
(3) Bouncing of a droplet,
(4) Rupture of a liquid–vapour interface.

(1) There is fairly conclusive evidence that quiescent evaporation from a water surface does not cause charge separation (**6**), (**7**), (**8**). Violent evaporation accompanied by bubbling and ebullition may do so. Spontaneous homogeneous nucleation may or may not produce charged critical nuclei and all experiments seeking an answer here have proved inconclusive. This subject is explored at length in reference (**4**).

(3) True bouncing implies the impact of a droplet with a surface and its subsequent rebound without the transfer of mass across the interface. Bouncing of solid particles is known (**9**) to result in contact charging, but it is unlikely (**10**) that in the steam turbine a 'bouncing' drop often avoids fracture of its surface, and the case then

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becomes a special example of process (4) in the above list.

The authors believed that the most likely origin of electrostatic charging was (4), and to a less extent, (2), and these were investigated in the experiments now to be described.

2 APPARATUS AND EXPERIMENTAL WORK

A wet steam tunnel was constructed for which the work here reported was the first assignment. The tunnel is illustrated on the photograph (Fig. 1) which shows the general arrangement at the operating end. The essential features of the tunnel are as follows.

Test section: 7·62 cm square cross section × 37 cm long.
Both vertical walls are detachable and a series of access ports are provided on the upper and lower fixed walls.
Maximum steam velocity 290 m/s at 0·17 bar.

Provision was made for spraying water into the steam at a controlled rate to provide a wetness fraction of 10 per cent maximum. This facility was not employed in this work.

Test section pressure measurements were indicated on a mercury column vacuum gauge, temperatures were measured using a copper–constantan thermocouple.

During commissioning velocity profiles were determined experimentally to check the uniformity of the test section velocity distribution.

The condensate was weighed to obtain the steam flow rate.

The working section of the tunnel, together with the contraction, were removed as a unit for tests employing air as working fluid. For these tests a large rotary compressor provided air at a small pressure above atmospheric with a velocity which could be controlled between 30 and 214 m/s.

The experimental work was directed towards investigating the following possible charging mechanisms:

(1) Primary atomization of liquid, i.e., liquid dispersed after aerodynamic detachment from an exposed surface,
(2) Secondary atomization, i.e., further aerodynamic subdivision of the liquid dispersed in (1),
(3) The flow of a dry gas over a surface,
(4) The flow of a liquid film over a surface.

Charging by Primary Atomization

A small brass blade was immersed in the dry steam flow (Fig. 2). Water was supplied to its surface through the tubular supporting stem and it broke away sporadically from the trailing edge and was entrained. This was believed to be a satisfactory simulation of corresponding events in the steam turbine. The charge separated was measured by two methods:

(*a*) The charge remaining on the blade was stored in a capacitor for a fixed period and then discharged through a ballistic galvanometer. This gives the average charging rate.
(*b*) The charge remaining on the blade was fed through a charge amplifier/voltage amplifier to a single channel pulse analyser and chart recorder to measure the magnitude of the individual pulses associated with the formation and departure of each droplet.

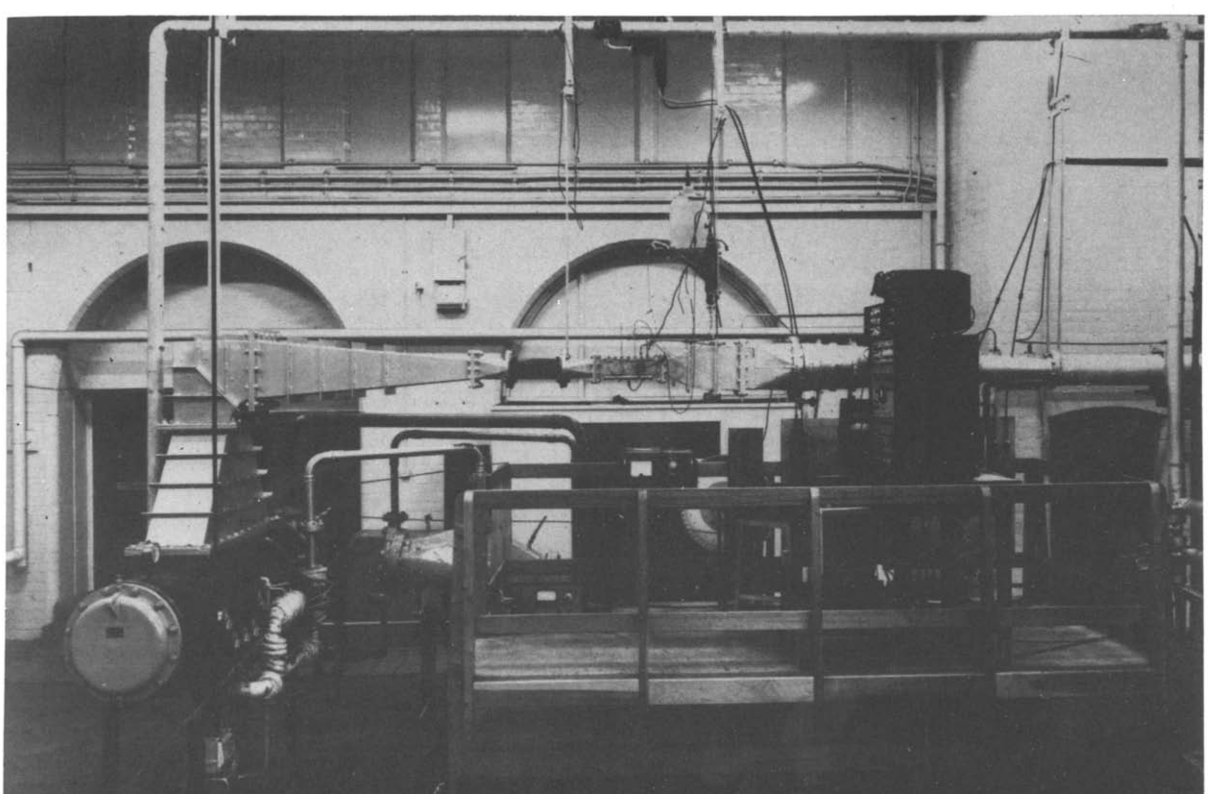
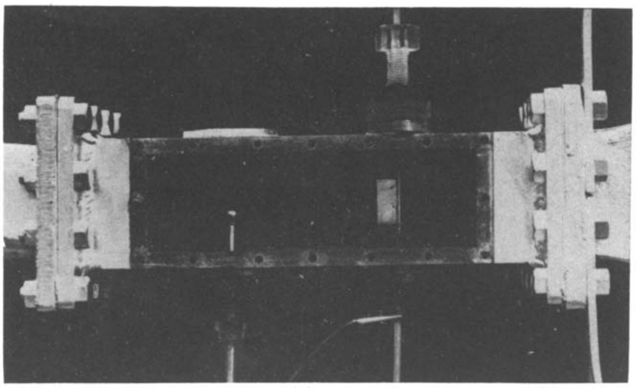
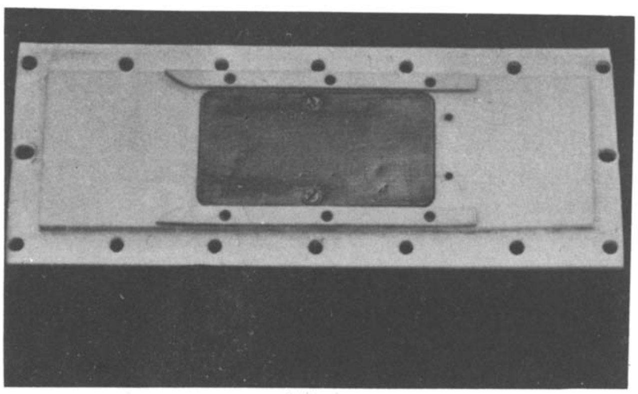


Fig. 1. Wet Steam Experimental Tunnel



(a)



(b)

Fig. 2. (a) Test section with front window removed showing brass blade and copper collecting sphere. (b) Detachable sidewall made of PTFE with inlaid copper plate

An attempt was made to record simultaneously a photographic image of a droplet leaving the blade trailing edge and the corresponding electrical pulse shown on the cathode ray oscilloscope by using a high-speed camera with two lenses. Only limited success resulted. Also, during preliminary trials several attempts were made to trap the entrained water which had separated from the blade so that the charge thereon could be compared with the charge on the blade. Several designs of collector were tried without success, it proving impossible to avoid some re-entrainment of the collected water.

Injection water was supplied from an overhead reservoir (seen on Fig. 1), the flow rate being measured by rotameter. Great care was taken to insulate the water system and to prevent vibration of the blade, which latter distorted the oscilloscope trace due to capacitance variation between blade and tunnel wall.

Tests similar to the above were conducted using air, the velocity of which was measured by a pitot tube situated near the centre of the working section.

Charging by Secondary Atomization

A spherical copper probe 1·2 cm diameter was inserted into the test section 11 cm downstream of the blade trailing edge from which water was breaking. The coarse water from the blade was atomized by the main steam (or air) flow, the degree of atomization depending on the steam (or air) velocity. A proportion of this atomized spray struck the probe and then evaporated off into the superheated environment if the water flow rate was small. At higher flow rates some was also shed from the leeward side of the sphere; and at still higher flows considerable stripping of droplets from the exposed periphery of the sphere was observed.

When droplets struck the probe they transferred thereto any charge they might carry, and these charge pulses were measured in the manner described in the preceding paragraph.

Screening and charge leakage problems were encountered during commissioning and were eventually solved.

Dry Steam Charging

Preliminary experiments were conducted to determine the order of magnitude of any such charging effect by using superheated steam with the spherical probe described above. Used later was an improved method consisting of a detachable sidewall made of PTFE into which a sheet of copper was inlaid to provide a flat interior surface to the working section.

A vibrating reed electrometer calibrated to register electrical currents within the range 10 nA–1 fA was used to measure the rate of flow of charge from the plate. Readings were taken of the current passing to earth when the plate was swept by superheated steam at various rates of flow. Similar tests were undertaken using air, but no provision existed for drying or cleaning the air.

Charging by Liquid Film Flow

For these experiments the tunnel working section was rotated through 90° about its axis of flow to bring the PTFE wall with the copper plate to the 'floor' of the section. A controlled flow of water from the supply system described above was supplied through a feed hole. An attempt made to recover the water leaving the trailing edge of the copper plate in order to measure its charge was unsuccessful because of the limited suction head available.

Charging currents were found to exceed the measuring capacity of the electrometer. Charge was therefore measured by finding the voltage drop across a 100 kΩ resistor when the charging current was passing to earth.

Observation of the water film showed that the plate was never completely covered with water.

3 RESULTS AND DISCUSSION

Primary Atomization Experiments

Attempts to measure the blade charging rate using the ballistic galvanometer were unsuccessful because of charge leakage problems. Leakage occurred along the water feed line and it was not found possible adequately to insulate the feed system. Leakage also occurred through a film of contamination on the insulation inside the working section. This could be removed but tended to be re-established on each occasion during start-up. The results obtained, though quantitatively unreliable, indicated positively that charge separation was occurring when water was stripped from the blade trailing edge.

High-speed photography yielded only limited information owing to the difficulty of relating on the photographic film the optical and electrical (CRO) records of a given event. When using air there was unmistakable

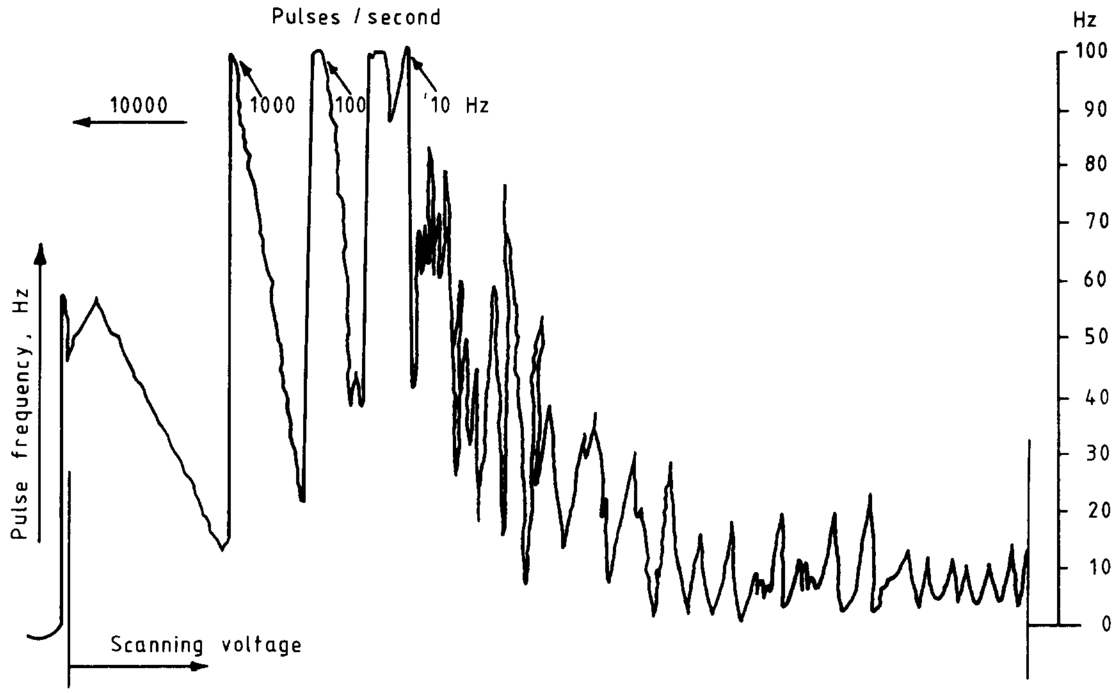


Fig. 3. Chart recording showing positive pulses from blade. Primary atomization. Steam test: 0·18 bar pressure. Steam velocity 285 m/s. Water flow rate 16 ml/min

evidence of secondary atomization. Photographic measurements of stable drop sizes were clearly consistent with the values expected from a critical Weber number of 13–22 (a range covering the views of most authorities) for the air velocities employed. When steam was used, evidence for secondary atomization was inconclusive.

Results from the pulse analyser were acceptable, and chart records of pulse amplitude versus pulse frequency were taken separately for both positive and negative pulses both with and without water flowing over the blade. Four charts for each test condition were therefore obtained and a representative chart is shown in Fig. 3. On these charts the abscissa indicates the instantaneous value of the scanning voltage and the ordinates the pulse frequency. Suitable calibration curves, together with the relevant charge amplifier data enable the findings to be presented as in Fig. 4. It should be observed that there is a change of frequency range in the Fig. 3 curves to promote maximum accuracy of reading. The results indicate the existence of two types of water-stripping process.

(a) When water was being supplied continuously to the blade a large number of droplets tended to be sprayed from the trailing edge resulting in many

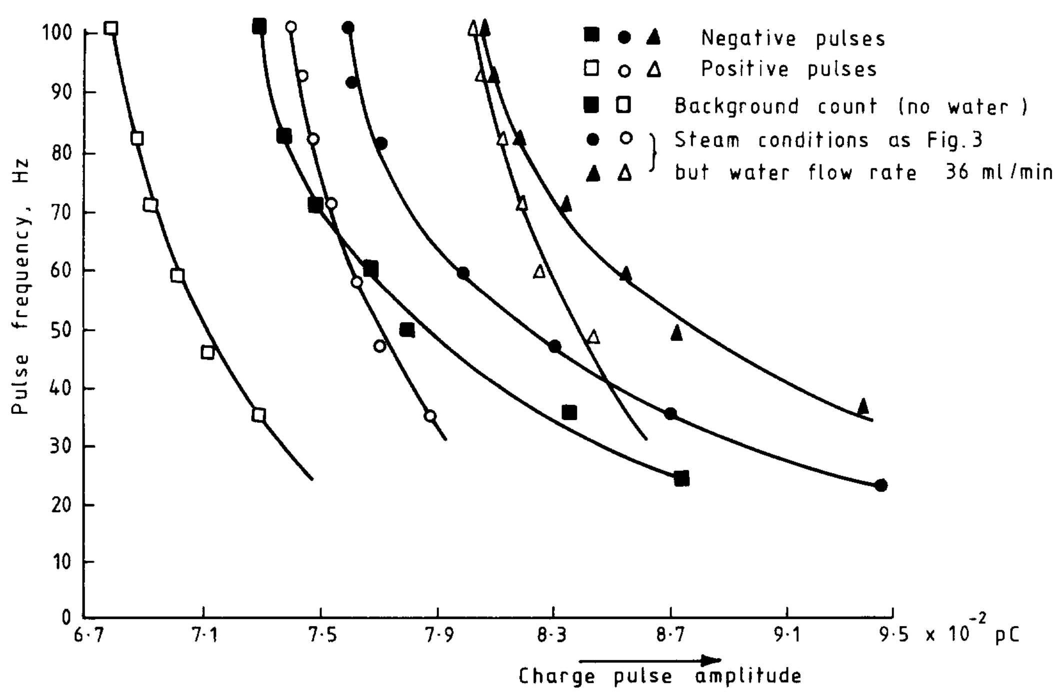


Fig. 4. Pulse frequency versus charge pulse amplitude. 0–100 pulses/s (section from charts)

small charge pulses of both polarities with a net tendency to leave a small negative charge on the blade. The frequency distributions suggest that the charge carried away by a departing droplet was dependent on the number of free electrons or ions available at its formation. Since such a number is necessarily random the charge acquired is statistical in magnitude.

(b) When the water supply had been disconnected and the blade was completing its drying out, larger droplets broke away and pulses up to 10 pC of unknown polarity were recorded. The charging mechanism was believed to be electrolytic and the relation: charge/diameter could not be determined.

Relating the above to the steam turbine and in view of the low values of charge per pulse, it is believed that electrification by primary atomization from blade stripping is likely to be low.

Secondary Atomization Experiments

(a) *Ballistic Galvanometer Measurements* Results for both air and steam are shown on Fig. 5. For air it is seen that the rate of negative charging of the spherical probe increased for all velocities exceeding about 55 m/s. At lower velocities there was an increase in the rate of positive charging. The greater the water flow rate from the upstream blade, the higher was the charge rate of the sphere for a given vapour velocity. Similar negative charging resulted from tests in the steam tunnel except that the charge rate remained small up to about 150 m/s after which it increased rapidly. Figure 6 shows the results obtained when tests were conducted using fixed values of air velocity and variable water flow rate, while Figs. 7, 8, and 9 show the variation in charge rate for both air and steam for a given water flow rate at varying gas velocities.

Considering these results it is evident from Figs. 5 and 6 that three regimes of charging can be identified:

(i) Air velocity < 55 m/s
(ii) Air velocity 55 to 170 m/s
(iii) Air (and steam) velocity > 170 m/s

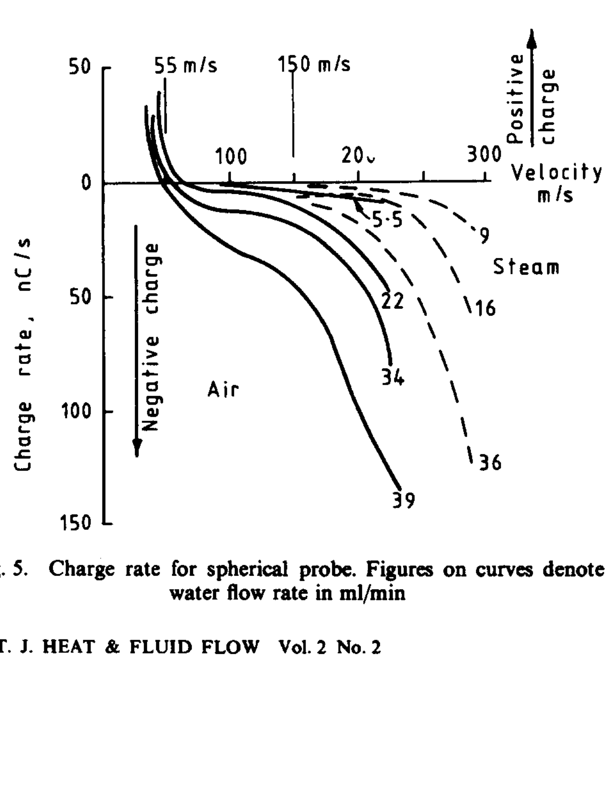


Fig. 5. Charge rate for spherical probe. Figures on curves denote water flow rate in ml/min

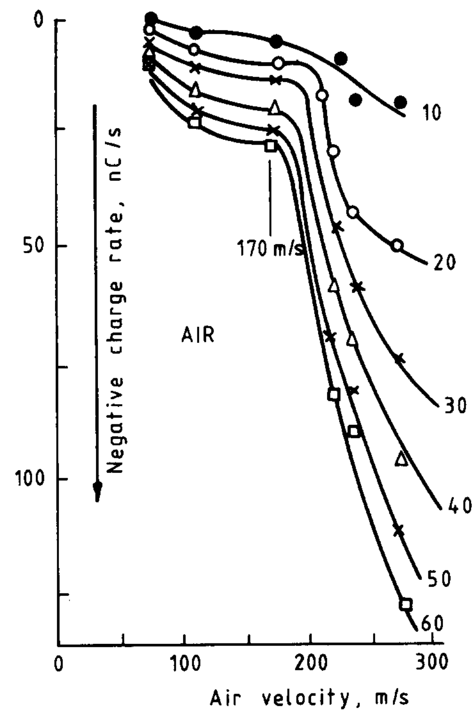


Fig. 6. Charge rate for spherical probe. Figures on curves denote water flow rate in ml/min

In regime (i) a positive charge occurred on the spherical probe which is believed to have been caused by the tendency of the probe to be struck by almost all the large drops, but fewer of the small drops owing to differences in collection efficiency. As the air velocity approaches 55 m/s the collection efficiency increases to a high value for droplets of all sizes and water also tends to break away from the centre of the blade edge rather than along its entire length. This encourages more uniform collection of both polarities of charge by the probe and a reduction to zero of the net charge.

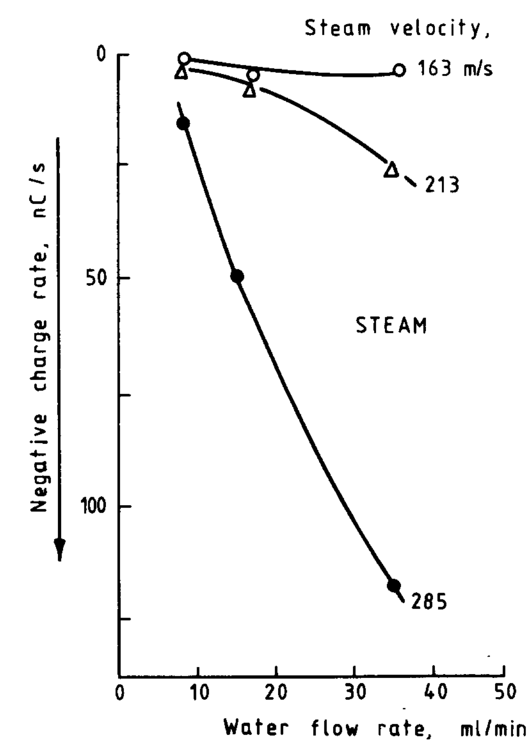


Fig. 7. Charge rate for spherical probe

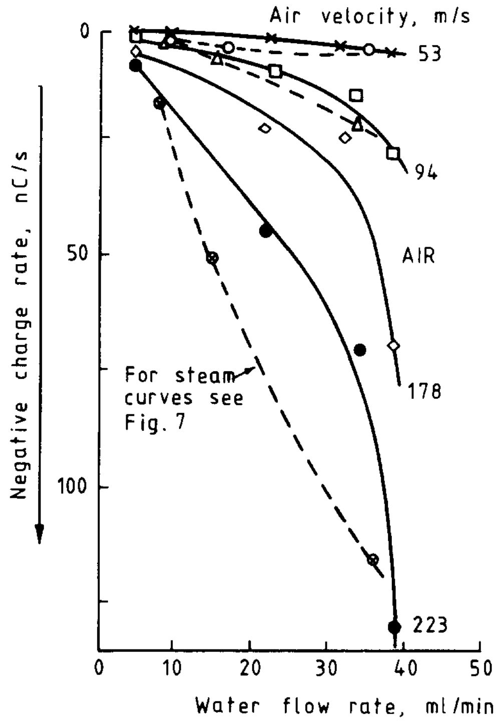


Fig. 8. Charge rate for spherical probe

In regime (ii) when the velocity exceeds 55 m/s some stripping of water occurs from the equator of the sphere perpendicular to the flow which is believed to cause a moderate negative charging rate of less than 16·7 nC/s for all water flow rates up to air velocities of approximately 170 m/s. The negative charge arises as a consequence of the transfer away from the sphere of positive charge by the larger masses of water stripped away.

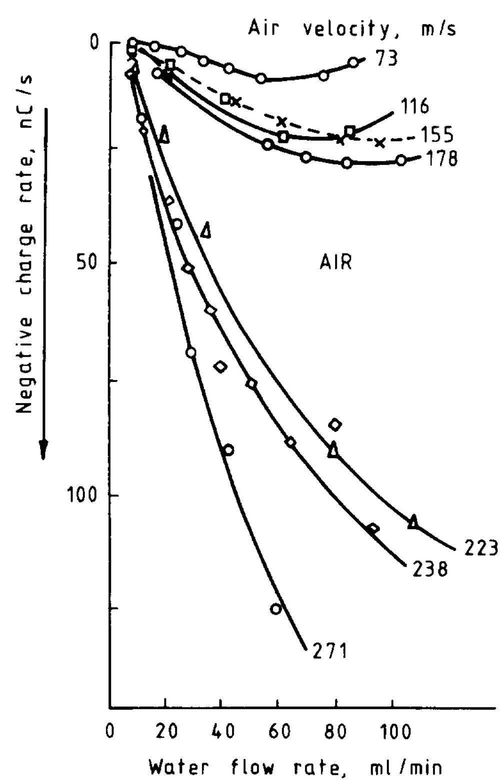


Fig. 9. Charge rate for spherical probe

In regime (iii) the charge rate rose rapidly with air (and steam) velocity for reasons that are imperfectly understood. Cathode ray oscilloscope observations showed that large pulses (*c*. 20 pC) were being received and it is thought that these might result from impact shattering of drops as they strike the probe at high velocity. Increasing velocity may be expected to increase the extent of fragmentation. This subject is explored in detail in reference (**4**). The measurement of rapid charging rates was made less precise because (*a*) the time taken for a maximum charge of 133 nC to accumulate could be commensurate with the human error involved in switching at high charge rates, and (*b*) when the charge stored in the capacitor was released to earth through the galvanometer the probe remained connected thereto and continued to pass charge through the galvanometer. At high charge rates this would cause a fictitious increase in the charge rate reading.

(b) *Pulse Analyser Measurements* Chart recordings were taken for both negative and positive pulses both with and without water flowing from the blade, for steam flow only. The general appearance of the charts is similar to those shown in Fig. 3. The processed results giving pulse charge against pulse frequency are plotted on a logarithmic probability basis, and Fig. 10 shows a representative case. A general comparison of all cases is shown in Figs. 11 and 12 and shows the following:

(i) The negative pulses from the sphere tended to have a slightly greater amplitude than the positive pulses.

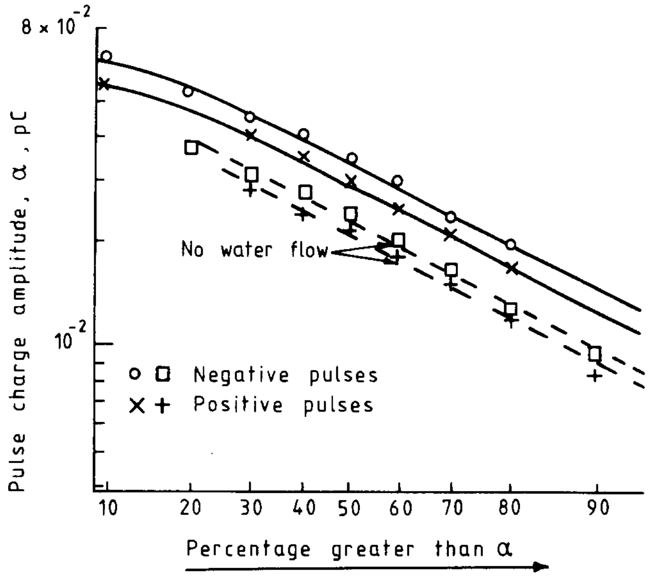


Fig. 10. Distribution of charge pulse amplitude given out by spherical probe. Mean steam velocity 163 m/s. Water flow rate 36 ml/min. Steam pressure 0·33 bar

Test number	1	2	3	4	5	6	7	8	9
Steam velocity m/s		285			213			163	
Water flow rate ml/min	36	16	7	36	16	9	36	18	9
Test section Pressure bar		0·182			0·262			0·332	

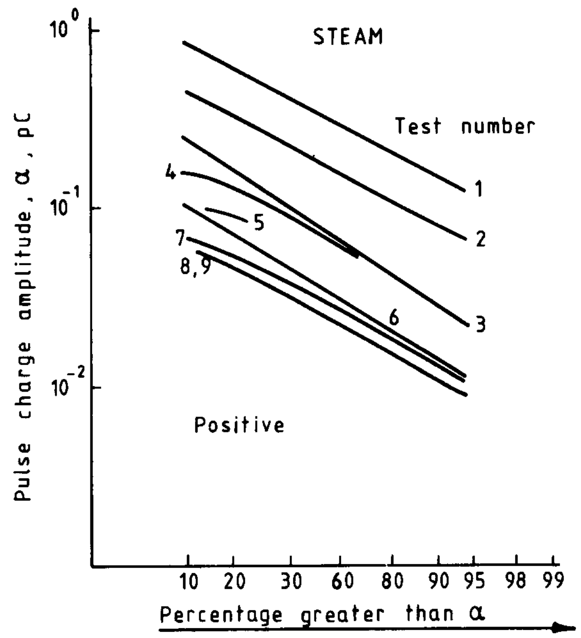


Fig. 11. Charge pulse distribution

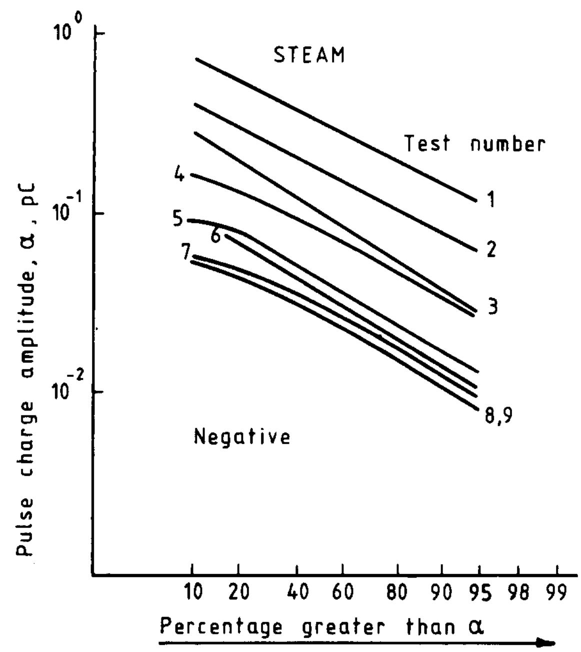


Fig. 12. Charge pulse distribution

(ii) The amplitude of both positive and negative pulses increased with increase of steam velocity or increase in water flow rate.

(iii) The difference in amplitude between positive and negative pulses decreased as the steam velocity increased.

(iv) At the maximum steam velocity employed the amplitude of the pulses from the sphere were of the same order as those from the blade. However, as the steam velocity increased, the amplitude of the pulses from the spherical probe became much larger than those from the blade, eventually exceeding them by a factor of ten.

(v) The corresponding positive and negative curves have the same slope which indicates similarity in the frequency distribution for both polarities.

(vi) The slopes of all the curves are similar but the slope tends to decline with increase of water flow or steam velocity. Diminishing slope implies increasing size uniformity of pulse.

Dry Steam Charging

Three tests were conducted using the copper plate mounted in the PTFE sidewall and three additional tests using the spherical probe. Attempts were made using air, but were erratic due to moisture and particles of dust. The average current from the copper plate immersed within a superheated steam flow was 0·93 pA/cm^2 of exposed surface. This was a steady flow of 1·03 pC/cm^2 s of positive charge indicating that an equal amount of negative charge was conducted away by the steam.

The length of time needed to establish a steady maximum current was often one hour or longer. If water was injected to wet the plate and then turned off it took some time to re-establish the steady plate current and often there would be a temporary reversal of polarity. These effects were due to surface contamination and the action of injected water was to wash the plate. Following washing the plate re-acquired its normal film of contaminant and oxide. The effects just described occurred mainly on the new copper plate which was regularly cleaned, but rarely on the spherical probe which was heavily contaminated from many months of use and probably incapable of being cleaned directly by flowing water. Supporting evidence is found in references **(11)** and **(13)**.

Although there are two interfaces (copper/water and water/steam) involved when water is flowing over the copper plate, the charging effect on the water/steam interface is unimportant **(12)** and it is reasonable to suppose that turbine rotors operating in wholly dry steam only acquire a weak electrostatic charge.

Charging by Liquid Film Flow

In the steam turbine the amount of water flowing, probably mainly in the form of rivulets, is unlikely to be sufficient to produce a large charge on the rotor in comparison with other charging effects.

4 CONCLUSIONS

The principal conclusions are as follows.

(1) There are two modes of formation of electrostatic charges both arising from the existence of the electrical double layer: charging arising from the fracture of liquid surface, and charging arising from bouncing contact. Both are possible in the steam turbine; but droplet bouncing is a fairly rare occurrence and most of the charge arises from fracture of liquid. In the steam turbine the principal charging mechanisms are:
  (a) the impact of a drop upon a surface followed by fracture and the dispersal of small fragments,
  (b) primary atomization of liquid swept from an exposed trailing edge on the rotor, usually the blade,
  (c) aerodynamic fracture of drops in flight which become charged and subsequently transfer charge to surfaces they strike,
  (d) by a film of water flowing over a surface, and

(e) dry steam charging which is not significant in magnitude.

The net charge on the rotor at any steady-state condition is determined by the difference in rates of charging and discharging. Discharging proceeds by

(a) Transport of charge by drops stripping from rotor,
(b) corona for highly charged rotors, and
(c) by leakage along surface and internal conducting paths.

(2) The polarity of the charge is dependent upon the condition of the surface and may be reversed if the surface is dirty or contaminated.

(3) The time during which water remains in contact with the metal is significant, both because a longer time encourages relaxation of the charge and because alternate wetting and drying promotes changes in polarity.

(4) This paper has been concerned with the generation of electrostatic charge, not with the manner in which it may affect the performance of the turbine. It is known from a number of sources that charges influence, among other things, the size of the critical nucleus at nucleation, the effective surface tension of drops, the rate of diffusional deposition of fog droplets, the coalescence behaviour of entrained water, and the trajectories of drops in flight. It is believed that the performance of a turbine would be substantially the same if the rotor and working fluid remained everywhere electrically neutral. Nevertheless, one cannot be sure, and it would be of value to know if, for example, critical nuclei are electrically neutral. The suggestion has also been made (references (**1**), (**4**), and elsewhere) that blade erosion rate is influenced by electrostatic charging, or that erosion rate might be experimentally related, for monitoring purposes, to charging rate since both are functions of steam impact velocity.

5 ACKNOWLEDGEMENTS

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APPENDIX

The Lenard Effect

Lenard (1892) explained the electrification of fine spray in the vicinity of waterfalls. Very small droplets were found to be negatively charged and larger drops, together with the surface of the bulk liquid, were found to be positively charged. The effect is due to asymmetric breakage of the electrical double layer residing in the air/water interface.