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STREAMING CURRENTS IN TURBULENT FLOWS AND METAL CAPILLARIES

III. EXPERIMENT (1). AIM AND PROCEDURE

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Synopsis

With a preliminary liquid high tension generator a tension of 70 kV at a current of 0.1μA has been reached.

The measurements on the streaming current have been carried out by means of a simple compensation method which allows us to detect currents up from 3×10^{-13}A. It is possible to distinguish the contributions of the pure streaming current and the exchange of charge between liquid and tube wall.

Measurements have been performed with refined gasoline flowing through a number of brass capillaries varying in length from 15 to 60 mm, in diameter from 0.5 to 3 mm, and of different cross-section shape, entrance disturbance and wall roughness.

It appeared from introductory measurements that a stationary situation may not be reached until after some minutes.

1. *Purpose of the experiments.* It has already been pointed out that the object was to measure the mean charge density $\bar{\rho}$ which occurs in a liquid as a result of the phenomenon of the streaming current, after the liquid has flown through a tube. Especially $\bar{\rho}$ as a function of Reynolds' number *Re*, tube dimensions and temperature would be measured for a turbulent flow of a badly conducting liquid in a metal tube. This experiment was part of the development program of an electrostatic h.t. generator in which the high tension is built up by the streaming current.

The preliminary apparatus, mentioned in I is drawn in fig. III-1. The liquid is pumped around in a closed circuit. From the pump it flows through a diaphragm, consisting of a number of parallel capillaries in which it is charged; it then flows through a glass tube into a metal sphere where it leaves its charge by flowing along the sphere's inner surface. Through another glass tube the liquid flows back to the pump. The metal sphere gets a high tension with respect to the diaphragm which is earthed.

It is clear that the liquid must be badly conducting because its resistance lies between sphere and earth. Yet $\bar{\rho}$ must be high, which implies that a highly specific adsorption on the wall of the diaphragm capillaries is needed for one of the types of ions that are present in the liquid.

In the apparatus iron diaphragms were used varying in length from 2 to 40 mm and containing 120 capillaries of 2 mm diameter. The high tension is measured with a rotating voltmeter (essentially a field strength meter); the liquid flow with a differential transformer driven by a "flowtrol"; the short circuit current by a Zernike galvanometer or by the potential fall it causes over the high input resistance of a vacuum tube voltmeter. With refined gasoline at a flow of 3 l/sec, the current was 0.1 μA (i.e. $\bar{\rho} = 3 \times 10^{-1}$ C/cm^3) and the tension 50 kV, though with special precautions higher currents (up to 0.2 μA) and tensions (up to 70 kV) were reached.

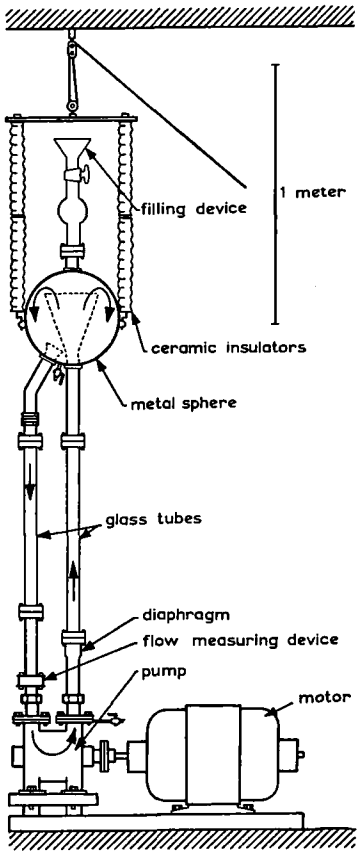

Fig. III-1. High tension electrostatic generator.

There appeared to be only a very slight dependence on the diaphragms used and it was expected that much larger $\bar{\rho}$ values, resulting in higher current and tension could be reached if the factors on which $\bar{\rho}$ depends were better known.

Therefore a series of experiments was proposed with smaller amounts of liquid and with only 1 capillary at a time.

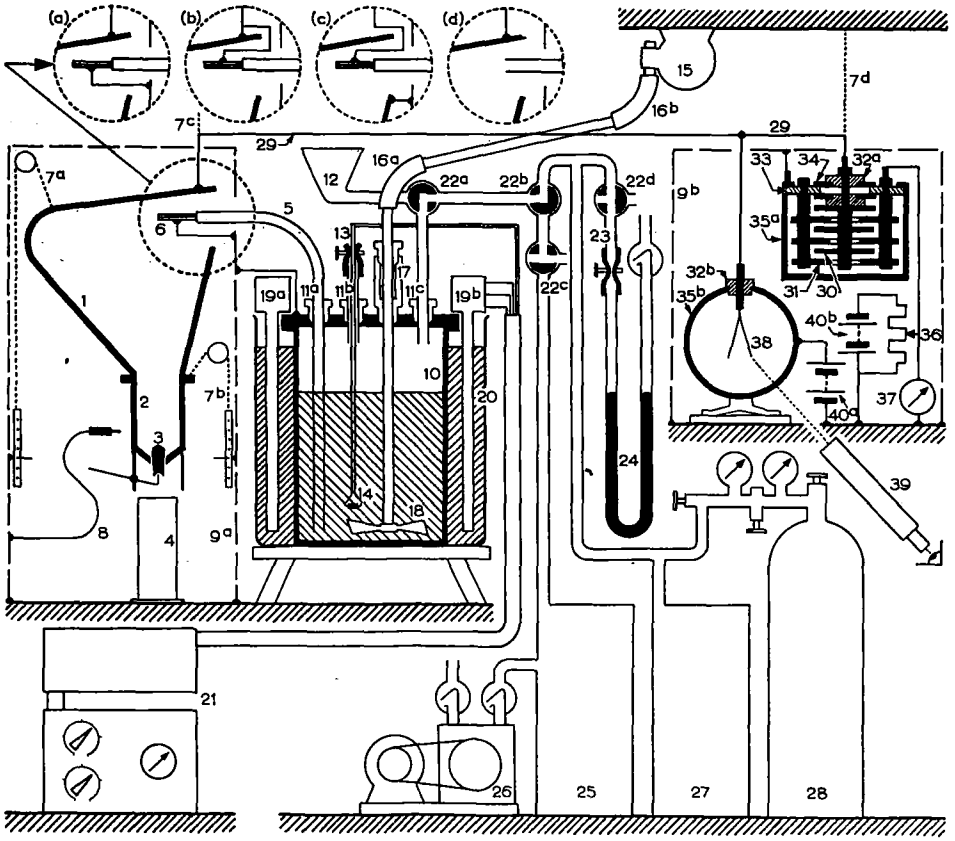

Fig. III-2. Equipment for measuring the streaming current.

1. funnel
2. collecting vessel
3. draining stop
4. measuring glass
5. glass tube
6. metal capillary
7a–d. nylon wires
8. discharging device
9a–b. Faraday cages
10. storage vessel
11a–c. Finkelstein inlets
12. filling device
13. air outlet for refilling
14. thermistor
15. stirring motor
16a–b. flexible shaft couplings
17. akulon bearings with asbestos packing
18. stirring vane
19a–b. heaters
20. watertank
21. link panel and thermostate
22a–d. air cocks
23. air damping
24. mercury manometer
25. vacuum vessel
26. vacuum pump
27. pressure vessel
28. cylinder with compressed air
29. highly insulated line
30. highly insulated condensor plates
31. other condenser plates
32a–b. amber insulation
33. perspex insulation
34. guard ring connected with (35a)
35a–b. screenings
36. potentiometer
37. voltmeter
38. electrometer leaves
39. magnifying inspection tube
40a–b. batteries

2. *Measuring equipment and experimental procedure.* Measuring the streaming current. The measurements of the streaming current were made with the apparatus shown in fig. III-2. The liquid was stored in a vessel (10) of metal (nickle plated steel) which was earthed so as to be certain that the liquid had no electric charge. From a cylinder (28) compressed air or nitrogen was brought into the pressure vessel (27) up to the desired pressure, which could be read on a mercury manometer (24). By opening a cock (22*b*), compressed air was brought above the liquid level, causing the liquid to flow through the glass tube (5) on the end of which, by a simple conical junction, a metal capillary (6) could be fixed. Flowing through (5) and (6) the liquid was charged as a consequence of the phenomenon of the streaming current. The charged liquid was gathered by a funnel (1), which collected also scattered liquid drops, and flowed into the collecting vessel (2).

Next the charge of the liquid must be measured. For this purpose (1) and (2) were made of metal (nickle covered iron and brass) and suspended on nylon wires (7) in a screening cage. The line (29) connected (1) and (2) with an electrometer (38) and one set of plates (30) of an air dielectric-condenser; the other plates (31) could be raised or lowered in potential to earth by an ordinary potentiometer circuit (36). If the liquid flows into (2), then the indication of the electrometer alters. By turning, however, the potentiometer (36), the alteration in indication can be made undone, with the consequence that (29) remains on earth potential and that a potential difference occurs between (30) and (31), proportional to the liquid's charge, gathered now on (30).

If, besides the symbols used in I, ΔV is the voltage rise of (31) in the time Δt and C is the capacity between (30) and (31), then $Q\Delta t$ is the volume of the liquid that has flown into (2) and $-C\Delta V$ is the charge on (30); therefore the mean charge density in the liquid is:

$$\bar{\rho} = -C\Delta V/Q\Delta t \tag{III-1}$$

and Reynolds number (cf. I):

$$Re = 2R\bar{v}/\nu = 2Q/\nu\pi R \tag{III-2}$$

for a round capillary, and

$$Re = 4d\bar{v}/\nu = 2Q/\nu B \tag{III-3}$$

for a flat one (if the flow is turbulent and $B \gg d$). The values of C and ν being known and that of ΔV, Δt and $Q\Delta t$ being measured, $\bar{\rho}$ and Re can be calculated.

At the end of a measurement, the liquid flow was stopped by connecting (10) with open air by (22*b* and *c*) or by connecting it with a vacuum vessel (25). The liquid was drained into a measuring glass by lifting a conus (3) in the bottom of (2). Before beginning a new measurement, the potentiometer (36) was turned to zero voltage and the line (29) was discharged by touching (2) with an earthed wire (8).

The vacuum can also be used to boil off dissolved air from the liquid at room temperature.

The parts in the dotted circle of fig. III-2 may be connected in different ways, as shown in the 4 circles called (*a*), (*b*), (*c*) and (*d*). By means of these connections it is possible to discern charges which are produced in glass tube and metal capillary respectively.

Distinguishing the measured charges. Besides case (*a*) of fig. III-2 also the situations (*b*), (*c*) and (*d*) will be considered below.

If the charge that results in the collecting vessel at a certain liquid flow after a certain time is ω_g if only the glass tube is present and $\omega_g + \omega_m$ if glass tube and metal capillary are in use, the following two cases may be discerned.

A. No wall current exists, only a pure streaming current is present (fig. III-3A). In situations (*a*) and (*b*) of fig. III-2 the charge measured by the electrometer system is the charge gathered in the collecting vessel, i.e. $\omega_g + \omega_m$. In situation (*c*) the collecting vessel is not connected to the electrometer and no charge is measured. In situation (*d*) only ω_g exists.

B. The charge ω_m is supplied by the wall of the metal capillary (fig. III-3B). In situation (*a*) again $\omega_g + \omega_m$ is measured. In situation (*b*), however, $\omega_m + \omega_g$ is furnished by the liquid to the collecting vessel and so to the electrometer, but the capillary receives a charge ω_m from the electrometer system and as a result only ω_g is measured. In situation (*c*) only the capillary is connected with the electrometer and the measured charge is $-\omega_m$. In situation (*d*) ω_g is measured. The results have been summarized in the equations (III-4).

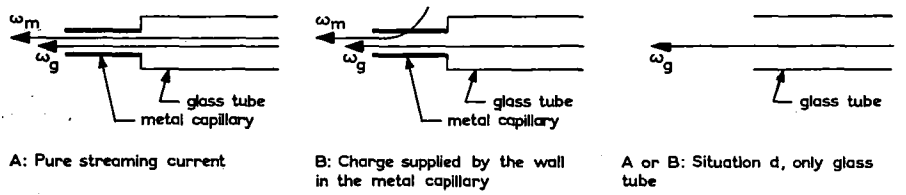

Fig. III-3. Illustration to the method of discriminating between the charges caused by the glass tube and by the metal capillary and to the method of examining whether the charge in the metal capillary is supplied by the wall or not.

Situations of fig. III-2	*A*, pure streaming current	*B*, streaming current fully supplied by wall current	
(*a*)	$\omega_a = \omega_g + \omega_m$	$\omega_a = \omega_g + \omega_m$	(III-4)
(*b*)	$\omega_b = \omega_g + \omega_m$	$\omega_b = \omega_g$	
(*c*)	$\omega_c = 0$	$\omega_c = -\omega_m$	
(*d*)	$\omega_d = \omega_g$	$\omega_d = \omega_g$	

We have the check $\omega_a + \omega_c = \omega_0$. In practice often $\omega_g \ll \omega_m$ hence $\omega_a \approx \omega_m$. Strictly speaking for ω_m one must read the charge produced in

the capillary by the liquid that has been charged beforehand in the glass tube by ω_g, but $\omega_g \ll \omega_m$ allows to neglect this.

The experiments show clearly that in our case situation B is realized, since $\omega_c \neq 0$ and has the sign opposite to that of ω_a; furthermore measurements of ω_b fit to measurements of ω_d.

The electrical leaks. These require a special inspection and can be measured by means of the equipment itself.

The requirements are two: 1°. the time constant of insulations and capacities must be large with respect to the time that is required for the experimeter to turn the potentiometer in the right position, 2°. the battery current through the electrometer insulation must be small compared with the smallest current that can be detected and which is 3×10^{-13} A.

These requirements are amply fulfilled.

The thermostate. For measurements at temperatures higher than room temperature the storage vessel (10) is placed in a water tank (20) that can be held at constant temperature by heaters, switched by a thermostate. The resistance of a thermistor (14), suspended in the liquid is, in a d.c. Wheatstone bridge, compared with one of a set of standard resistances. The total standard resistance can be made equal to the resistance the thermistor would have at the desired temperature. As long as the desired temperature is not reached, a difference tension appears across the bridge. This difference tension is amplified in a balanced d.c. amplifier. The amplified difference tension switches the heaters (19) and in addition it can be read on a panel-meter calibrated in degrees centigrade.

For measurements below room temperature, the thermostate as such cannot be used, but temperature can be read on it. The stirrer (18) ascertains a homogeneous temperature in the liquid.

If the liquid is flowing the capillary (6) takes the temperature of the liquid within a few minutes.

Capillaries. Measurements have been performed on 22 brass capillaries of different length (15–60 mm), diameter (0.5–3 mm), cross-section (round and rectangular), inner surface condition (smooth and rough) and entrance disturbance (sudden and gradual entry).

Also some measurements were carried out on the glass tube (5) of fig. III-2, which has a length of 600 mm and a diameter of 6.4 mm, a brass tube of the same dimensions and some glass and iron capillaries.

Liquids. The following liquids were used.

Liq. 1: aromate free refined gasoline with about 0.01% of a Mg-sulphonate with a long carbon chain, which, however, tended to precipitate on the wall of vessels and tubes.

Liq. 2: refined gasoline only, containing enough substances in it to produce a streaming current; this liquid contained probably a trace of the sulphonate left in the vessels. The charge measured with this liquid was

lower than with liq. 1 and decreased gradually in the course of some weeks and after a rise in temperature did so suddenly.

Liq. 3: the exhausted liq. 2, reactivated with 0.5% synthetic soap. This mixture also showed a decrease of charge, especially during the first days.

Liq. 4: refined gasoline with about 0.05% of the same sulphonate as with liq. 1.

With regard to the remarks in 3 it is obvious that the exactness of these concentrations and the purety of the solutions could not always be relied upon. The used mixtures are chemically so far from well determined and their behaviour in keeping, treating and heating them is so precarious that the measurements must be considered mainly as illustrations of the method. Therefore, conslusions from these measurements must be accepted with reserve.

The values of dielectric constant ε, electric conductivity σ and relaxation time τ of the liquids were measured with a special liquid condenser consisting of two coaxial cylinders kept close together with a perspex insulator that had no contact with the liquid. There were three measurements, namely the resistance R_{liq} (with d.c.) and the capacity C_{liq} of the condenser filled with liquid and the capacity C_{air} of the empty condenser (both with 50 c/s a.c.). We thus get

$$\begin{aligned} \varepsilon &= C_{liq}/C_{air}, \\ R_{liq}C_{liq} = \tau &= \varepsilon/4\pi\sigma = C_{liq}/4\pi\sigma C_{air}, \\ \sigma &= 1/4\pi R_{liq}C_{air}. \end{aligned}$$

So with this method of calculation of σ no dimensions of the capacitor need be measured.

For liq. 1 τ was also measured directly with a neon bulb flash method. For ε was found 1.94 at 20°C; for σ:

$$\begin{aligned} &\text{liq 1: } \sigma = 1.8 \times 10^{-12}\ \Omega^{-1}\ \text{cm}^{-1}\ (\tau = 0.1\ \text{sec}), \\ &\text{liq 2: } \sigma = 1.2 \times 10^{-12}\ \Omega^{-1}\ \text{cm}^{-1}, \\ &\text{liq 3: } \sigma = \quad\ 10^{-10}\ \Omega^{-1}\ \text{cm}^{-1}, \\ &\text{liq 4: } \sigma = 1.0 \times 10^{-11}\ \Omega^{-1}\ \text{cm}^{-1}. \end{aligned}$$

The measurements of the viscosity $\nu(T)$ were performed with a simple capillary viscometer placed in a water bath.

3. *Additional results from introductory measurements.* Preliminary remarks concerning measurements of $\bar{\rho}$. Values of $\bar{\rho}$ collected in different figures cannot always be compared, because very small concentrations of admixtures and alterations of these concentrations, in consequence of partial evaporation of the liquid, solution of air in it, presence of dust particles and reactions with the materials of vessels and tubes can strongly influence the streaming current.

Yet care was taken to minimize these effects by avoiding materials such as grease and rubber that dissolve in the liquid and by keeping the liquid in the closed storage vessel for several hours at increased temperature before doing measurements on it.

Furthermore some decrease in the values of $\bar{\rho}$ was always found after a large number of measurements.

With liq. 1 and liq. 4 a negative $\bar{\rho}$ was found, with liq. 2 and liq. 3 a positive one. Apart from a difference in the composition of the liquid, the material of the storage vessel may be one of the causes, for with liq. 1 a glass vessel was used, with the other liquids the metal one of fig. III-2. Liq. 3 appeared to give a negative charge just after it had been poured into the metal storage vessel from the glass vessel in which it had been made. Within a few hours this charge turned positive until, after one day, it had got a value that remained only slightly variable and which was not influenced by keeping it again in a glass vessel for some time.

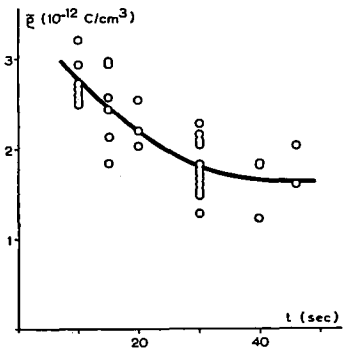

Fig. III-4. Charging effect of glass tube. Mean charge density in the liquid as a function of time duration of the measurement. Reynolds' number and temperature constant.

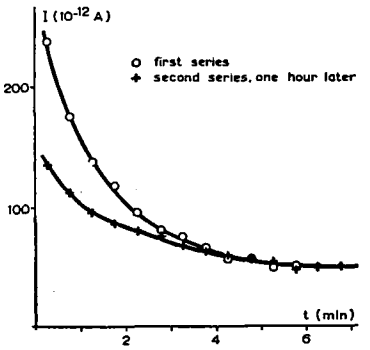

Fig. III-5. Starting effect in a brass capillary. Streaming current as a function of time in a capillary that had not been used for a long time. Reynolds' number and temperature constant.

Transient phenomena. Examining these was more a consequence of an inquiry for difficulties appearing when the equipment was not yet in its present form, than a special object of research. So there may be great differences in the results. The effect of the glass tube being charged by the liquid and discharging itself in the time between two measurements is shown in fig. III-4; the charge produced in the liquid is smaller the longer the liquid flows through the tube and seems to approach an equilibrium value. The phenomenon may perhaps be explained by assuming that the streaming current is in the first tens of seconds at least partially supplied by the wall of the glass tube but shades off then into the normal streaming current. So the time required to attain equilibrium between pulling down

the double layer and its recovery may be several seconds, while this stationary state may correspond with an appreciably lower space charge than if the liquid is at rest.

At the start of a set of measurements it takes often some time before a stationary situation is reached. In fig. III-5 an extreme case is shown of a capillary that had not been used for a long time, though it was stored all that time in refined gasoline. The current delivered by this capillary decreased with time until after about 6 minutes a constant value is reached. The cause of this phenomenon is unknown.

In other cases the first one or two measurements show a charge of opposite sign.

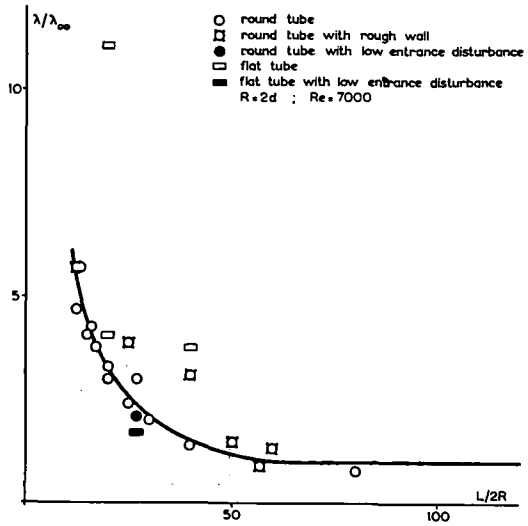

Fig. III-6. Ratio of friction number λ and value of λ for infinitely long tubes for tubes of different length to diameter ratio $L/2R$.

Pressure-loss in the fore-part of the tube. In plotting the Re, λ diagram (cf. I.5 and especially fig. I-7) for the different capillaries it was found that for tubes with relatively small $L/2R$ the λ values were higher than for long narrow tubes. Fig. III-6 shows the ratio of the experimentally found λ and the theoretical value for infinitely long tubes, as a function of $L/2R$ for $Re = 7000$. Tubes with $L/2R > 50$ appear to behave like infinitely long ones, which is in accordance with the fact that the velocity profile is not fully formed before $l/2R \approx 25$ to 100 (cf. II.4).

In relatively short tubes a comparatively high pressure loss appears, which is highest if the tube has a rough inner surface, and smallest if the entrance disturbance is low.

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