An Absolute Charge Sensor for Fluid Electrification Measurements

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ABSTRACT

A new instrument, the Absolute Charge Sensor (ACS), has been developed that measures the net charge density entrained in a fluid flow, independent of the fluid's electrical properties, velocity, and any electrification processes within the instrument. Through a shielded sampling probe, the ACS periodically transfers a small volume of charged fluid to an electrically isolated Faraday cage with no fluid exiting. The charge density is calculated from the known filling flow rate and either the current or voltage, respectively measured by low or high impedance electrometers connected to the electrically isolated Faraday cage. The ACS overcomes the ambiguity in current or voltage measurements of probes placed into the fluid flow where it is impossible to separate contributions from impacting charge in the flow from charge separated at the probe interface by the very charge generation and transport processes that are under study. The instrument is typically operated to measure charge densities as low as a few \( \mu \text{C/m}^3 \) using a sampling flow rate of 0.18 cm\(^3\) with a sampling period on the order of 1 min. A Couette charger apparatus that simulates flow electrification processes in transformers and fuel pumps has been used to test the ACS using transformer oil or gasoline. Results show good correlation between the ACS and continuous flow measurements. In preparation for field tests of electrification charging of transformer components, laboratory tests were also performed in a pump driven flow loop. ACS measurements of charge density were made at the inlet and outlet of an oil drum electrically grounded through an electrometer. Charge density measurements in flows having Reynolds numbers as high as 3000 were in good agreement with the charge conservation law, i.e. the difference in convection currents into and out of the grounded oil drum equal the measured current through the electrometer.
1. INTRODUCTION

Electrification has been long recognized as a problem in the flow of petroleum liquids in pipes, through filters, and in charge accumulation in storage tanks [1]. With changes in the chemical make-up of insulating liquids used to both transfer heat and/or withstand high electric stress, the use of new dielectric materials such as polymers and cellulosic materials, and an increase in the flow speeds for greater cooling, the electrification problem has recently arisen in electric power apparatus [2] and in automotive fuel systems. Polymeric replacements for metal parts in automotive fuel lines, filters, and pumps, have caused flow electrification initiated discharges which are hazardous.

A number of failures of large oil cooled power transformers [3] and in a trichlorotrifluoroethane cooled HVDC valve [4, 5] have been attributed to flow-induced electrification. Oil is generally used to cool the windings of a power transformer with the flow either by forced or natural convection through a heat exchanger to dissipate the generated heat. The moving oil provides the transport of entrained charge separated at liquid/solid interfaces by physical, chemical, and electrical phenomena. Moving transformer oil generally entrains positive charge in the flow leaving the counter negative charge fixed on the wall. An electric field is produced by the convection of charged oil through the transformer structure, with the oil playing the role of the belt of a Van de Graaff generator. Charge separation at interfaces between moving fluid and boundaries with the accumulation of charge on insulators or isolated conductors can lead to high-field strengths and electrical discharges. The potential builds up until the rate of charge accumulation equals the rate of charge leakage, or until spark discharges occur.

2. ELECTRIFICATION MEASUREMENT METHODS

There is no standard test procedure for evaluating the charging of flowing dielectric liquids, so that a number of testing methods have evolved.

2.1 MINISTATIC TESTER

A ministatic tester was adapted from electrification measurements in jet fuels to characterize the charge separation process in transformer oils by measuring the electrostatic charging tendency in forcing oil through standard filter paper, a high grade cellulose material chemically similar to transformer paper [6-8]. Actual transformer paper cannot be used because it is not sufficiently porous. The oil electrical charging tendency (ECT) is measured by the current from ground necessary to compensate double layer charge entrained in the fluid flow through the filter, or equivalently, measurement of the convection current to the fluid receiver grounded through a low impedance electrometer. The numerous pores in the filter increases the effective area of contact and thereby increases the streaming current. The measured current equals the charge density in the oil entering the receiver multiplied by the volume rate of flow through the filter. This apparatus is fast and simple for comparing the relative charging tendencies of different oil samples against a particular material filter. However, it does not seem well suited to providing parameters that characterize actual oil-liquid interfaces, especially under operating conditions with energization and/or with transients in temperature, moisture and concentration of other trace materials.

2.2 CONDUCTING PROBES

If a conducting probe is placed into the flow, measurement of the probe open circuit voltage or short circuit current does not provide an unambiguous value of charge density [9]. One may never be certain of the extent to which what is detected is due to impacting charge from the flow or from charge removed from the probe by the flow by the same charge separation process that is being studied. In a limiting case, flowing uncharged oil can strip charge off the probe giving a short circuit current or open circuit voltage. This objection can also be applied to a charge density probe composed of three equally spaced circular plates [10] where the outer electrodes were grounded and the potential of the floating center electrode was measured by a high impedance electrometer. Fluid flowing through the probe, even if entering uncharged, will separate some charge from the electrode surfaces raising the measured potential. There is no way to separate the effects of entering charge due to upstream flow electrification from charge separation within the probe.

2.3 ISOLATED TEST PIPE SECTIONS

Measurement of the current to an isolated metallic test pipe section gives the difference between the current leaving to that entering [4, 5, 11]. Generally, a pipe section simultaneously acts as a relaxation region for entering charge and as a charging region for charge separated within the pipe section. It is intended that the predominant current through the pipe be due to convection of the entrained charge density, but any nearby isolated sections that can rise in potential can lead to significant ohmic
currents. If either the inlet or outlet convection currents are not known, it is impossible to calculate the charge density at any point in the pipe from measurement of the pipe current alone. To force the entering charge density to be near zero, a large settling chamber is often placed just before the entrance of the test pipe, so that there is presumably a sufficient residence time of the fluid for charge relaxation to reach completion. However, such a relaxation region often requires an inconveniently large inventory of fluid and always leaves open the question of whether the fluid leaving the chamber does so without carrying charge. This charge could result from the separation and entrainment of charge at surfaces within the relaxation chamber, such as at exit ports, or simply be due to incomplete relaxation. Any unknown leakage currents to or from the test pipe section will further increase the difference between measured pipe current and the difference in convection currents.

A flow loop with isolated conducting pipe sections has been used to measure electrification production in the external oil circulation system of a power transformer [9]. Similar measurements in a laboratory pump driven flow loop will also be reported here in Section 3.5. To simulate the transformer duct region, insulating pressboard pipe models have also been used [8]. Measured variables include the streaming current exiting the pipe, leakage currents to conductors or segmented conductors surrounding the pressboard pipe, and the surface potential distribution along the pressboard pipe.

2.4 TANDEM CHARGE MONITOR

Another measurement approach without moving parts uses two identical shielded chambers through which the dielectric fluid passes in laminar flow [12]. Each chamber is virtually grounded through an electrometer which measures the current to the chamber. Each current is exponentially related to the ratio of fluid residence time in each chamber to the dielectric relaxation time so that the computed convection current depends only on the two measured currents. The measurement method is valid as long as the flow rate through the monitor is low enough that no charge is separated within the chambers. Thus for high speed flows the monitor is usually placed in a flow bypass loop.

2.5 CONTINUOUS FLOW CHARGE SAMPLING

The most direct way to measure the charge density in a fluid dielectric is to take a sample of charged fluid into a Faraday cage and measure the induced image charge via the current from ground required for a short circuited Faraday cage, or equivalently, measurement of the potential rise of the Faraday cage if it is open circuited. In pipe flow measurements, the four electrification stages of charge generation, transport, accumulation, and leakage, spatially overlap, making it difficult to sort out cause and effect. For basic studies, it is desirable to have a flow that is fully developed in both mechanical and electrical senses, which for insulating fluids requires an inconveniently long pipe length. The Couette flow system of coaxial cylinders in Figure 1 is closed on itself, so that all parameters must be independent of the azimuthal angle. What appears as a spatial transient in a developing pipe flow appears here as a temporal transient.

With the inner cylinder rotating, the Couette Charger (CC) isolates the charge generation stage and is a convenient source of net charge, similar to a current source in an electrical circuit [13, 14]. The charge density of the fluid is controlled by the rotational speed of the inner cylinder or by the magnitude and frequency of the applied voltage. The amount of charge in the flow is then delivered at a slow sampling flow rate, independent of the shaft speed. The output of the system is isolated from the fluid receiver by a short piece of insulated tubing and the output current is then measured by summing the currents from the ensuing metal pipe and the receiver. The pipe and metal receiver act as a Faraday cage so that once the charge exits the Couette Charger and enters the conducting pipe, it is immediately recorded by the electrometer, whether or not the charge remains entrained in the fluid or is conducted to the wall by relaxation, migration, or mixing. The recorded current is also not affected by charge generation by the flowing fluid within the Faraday cage, as additional charge entrained in the flow is balanced by the image charge remaining on the wall, so that there is no net change in total charge within the Faraday cage. Of course, the time during which a continuous measurement can be made is limited by the time to fill the fluid receiver.

3. THE ABSOLUTE CHARGE SENSOR

Central to sorting out electrification processes in the laboratory or in the field, is having an instrument for measuring the net charge density entrained in a liquid. Using the same sampling principles as with the continuous flow system of Figure 1, the Absolute Charge Sensor (ACS), also shown in Figure 1 and in more detail in Figure 2, can sample the flow with no net accumulation of
Figure 1.

CC apparatus with the ACS and continuous sampling flow system connected for simultaneous measurements. The outlet metal tube, connected to the OC through an insulating coupling, is electrically connected to the metal fluid receiver within a totally enclosed shield forming a Faraday cage virtually grounded through a current measuring electrometer.

fluid independent of the fluid’s electrical properties, velocity, and any electrification processes within the instrument [15–19].

3.1 ACS DESIGN

A schematic of the ACS is illustrated in Figure 2a. Fluid such as transformer oil or hydrocarbon fuel is drawn into an electrically conductive container as the metal bellows expands. The conductive container consists of the inner conductive conduit of the sampling probe, a metal bellows, one way check valves to allow the discharge of the sampled fluid to a downstream location, and the exit conduit which extends into the discharge line. A digital linear actuator (stepper motor) connected to the metal bellows by an insulating coupling withdraws the bellows end with a constant velocity during the filling process. The position of the bellows end is measured by a mechanically coupled potentiometer and the motions controlled by a feedback circuit. As the ACS is sampling fluid, either the voltage or the current is measured by a high or low impedance electrometer respectively, connected across the electrical terminals. Once the measurement is complete, the fluid is expelled through the exit check valve and conduit by reversing the direction of the actuator to compress the bellows volume. Due to flow electrification within the ACS, the fluid becomes charged as it enters and leaves the ACS, but as will be more extensively discussed, this internal charging has no effect on the charge density measurement as the measurement is made only during the fluid intake interval with the exit check valve closed so that no charged fluid is leaving. The valves and exit conduit are only necessary if the fluid is to be returned to a downstream location or to a relaxation region. If enough time is allowed for the charged exiting fluid to relax or wash away before the next measurement, the fluid may be returned through the sampling probe. The instrument samples a small amount of fluid and replaces it after the measurement, with no net accumulation of fluid.

A grounded shield surrounds the conductive Faraday cage container to shield it from external electric fields and to isolate the inner conductive conduit of the sampling probe from possible electrification processes occurring on the external probe surface. The currents separated by these electrification processes are not measured because the outer conductive conduit of the sampling probe is part of the grounded shield which is insulated from the inner conduit by an insulating sleeve such as Teflon™ which also forms a fluid seal between the two. Details of flush and recessed probes are shown in Figure 3. To virtually eliminate any charge being induced on the inner conductive conduit of the sampling probe by fields present in the sampling area of interest, the inner conduit can be recessed a distance on the order of the sampling tube diameter at the entrance of the probe as in Figure 3b. It is also necessary to recess the inner conduit when the ACS is used to sample fluid that is moving with a high velocity to isolate the end of the inner conduit from electrification currents caused by fluid motion. In some applications, a
Figure 2.
(a) Electrical and mechanical schematic and (b) diagram of the first version of the ACS.

ninety degree bend of the end of the sampling probe as in Figure 2a may reduce the coupling to the electric fields and the effects of electrification from the high velocity fluid but this complicates probe installation from outside the pipe. By recessing the inner conduit a small amount, a small error signal results from electrification of the fluid as it passes through the tip of the probe during the filling cycle. This is because there is now a slight amount of charge introduced into the fluid from electrification along the short exposed length of the outer conduit. The insulating sleeve is also further slightly recessed behind the inner probe to minimize contact with the sampled oil as polymer surfaces generally separate more charge than the metal surface of the outer probe. The error signal is then typically less than 1 \( \mu \text{C/m}^3 \). If the insulating sleeve is not recessed the error signal can exceed 5 \( \mu \text{C/m}^3 \). When the fluid velocity is small or when large electric fields are not present, it is not necessary to recess the inner conduit of the probe so that there is negligible error signal. In energization or high speed flow measurements the charge density is generally much larger than the error signal generated by the recessed probe.

The mechanical construction of the ACS for laboratory measurements is shown in Figure 2b. The check valves and metal bellows are mounted on a metal structure which is mechanically connected by an insulating base to the outer grounded case. The linear actuator consists of a threaded shaft which screws into the threaded rotor of the stepper motor so that when activated the shaft undergoes a linear motion. Rotation of the rotor is linked to a ten turn potentiometer by a mechanical coupling which gauges the rotor's linear position and thus the bellows volume. A triaxial connector is provided with the inner conductor connected to the conductive container, the middle conductor left unconnected, and the ground...
Representative tips of ACS probes for sampling charged fluid. Both the inner and outer conducting tubes are stainless steel separated by an insulating sleeve tubing such as Teflon™ (shaded). The outer probe acts as a shield and is grounded while the inner probe is electrically connected to the bellows volume as part of the Faraday cage. (a): Flush probe for sampling fluids where there are no strong electric fields or flow velocities. (b): Recessed inner probe with further recessed insulating sleeve showing representative dimensions for sampling fluids with high flow velocities or electric fields.

The ACS is being used to measure the charge density in power transformers and in automotive fuel pumps as schematically indicated in Figure 4.

### 3.2 ACS OPERATION

From experiments made famous by Faraday, it is known that a charged body introduced into a perfectly insulating volume surrounded by a conductive container will induce an opposite charge on the interior wall of the container. Thus, without actually being transported to the wall, the net charge induced onto the inner wall would be equal to but of opposite polarity to that in the fluid. Because the rate of accumulation of the charge so induced on the inner wall of the container comprises a capacitive electrical current that can be measured externally, it is then possible to measure this net charge by means of an external circuit having a sufficiently low impedance that the potential of the container would remain essentially zero relative to that of the surrounding shield. In actuality, the fluid is not a perfect insulator. Thus, in addition to the image charge induced on the wall, there are two other currents. One is a conduction current associated with the relaxation of the charged fluid. The other is a current due to flow induced electrification processes on the internal surface of the conductive container. Because the conductive container forms a Faraday cage, the current measured during the filling cycle is independent of processes that occur inside the Faraday cage whether they are due to imaging, charge relaxation, or electrification. The total charge within the Faraday cage volume and surface remains unchanged, equal to the total conductor connected to the grounded case. The potential of the middle conductor of the triaxial cable connecting the ACS and electrometer is controlled (guarded) by the electrometer to be the same as the center conductor so that cable leakage is minimized. Changes of capacitance due to bellows motion between the conductive container and the shield can affect the output signal in an undesirable manner. If there is a voltage \( V \) between the bellows and shield, a current \( i = C_dV/dt + VdC/dt \) will be detected as the bellows moves. A grounded disk which is mechanically connected to the movable end of the bellows is used to minimize the change in capacitance by maintaining the same relative distance between the movable end of the bellows and the grounded disk.
charge density \( \rho \), the terminal current \( i \), and the charge \( q \) induced on the highly conducting exterior surface of the conductive container. Conservation of charge requires that the transfer of charge into the inner container by the flow of liquid must equal the terminal current \( i \) plus the rate of change with respect to time of the charge \( q \) on the exterior surface of the conductive container.

\[
\rho Q = i + \frac{dq}{dt} \tag{1}
\]

On the intake of fluid there is negligible current where the surface \( S \) crosses the exit conduit as the output check valve is closed keeping the discharge fluid velocity zero during this interval and thus carries no current by convection. Any conduction current that might be due to the electric field from the net charge in the fluid is essentially parallel to the surface in the radial direction within the outlet conduit, and therefore does not contribute to Equation (1). Because the outer surface of the inner container and the inner surface of the surrounding shield are highly conducting, the capacitance \( C \) relates the charge \( q \) to voltage \( v \) between the inner container and shield

\[
q = C v \tag{2}
\]

With the detection electrometer attached to the terminals represented by a resistance \( R \), so that the terminal constraint is \( v = iR \), from Equation (1) and (2), the convection current becomes

\[
\rho Q = i + RC \frac{di}{dt} + Ri \frac{dC}{dt} \tag{3}
\]

For convenience the ACS has been designed so that \( C \) remains essentially constant during the expansion of the bellows. The movable grounded disk shield extension shown in Figure 2b limits the variation in capacitance caused by the bellows expansion so that the last term on the right of Equation (3) is negligible. For our ACS the capacitance with the guarded bellows maximally compressed was \( \approx 74 \) pF with an increase of \( \approx 0.15 \) pF/mm as the bellows was expanded. Over the maximum 11 mm length the bellows capacitance would only increase by 1.6 pF. An alternative to the movable shield extension to minimise variations in capacitance is to surround the bellows with a fixed conductive guard electrically and mechanically tied to the metal frame supporting the bellows. This however increases the capacitance between bellows and shield which can affect the detected signal by requiring a capacitive current comparable to the signal current. By using an electrometer of sufficiently low impedance such that the time constant \( RC \) is much less than the sampling period, the second term on the right of Equation (3) is also negligible so that for current-mode operation

\[
\rho = \frac{i}{Q} \tag{4}
\]
As the fluid flows into the conductive container the current $i$ measured by the external circuit is simply the net charge density $\rho$ of the sampled fluid multiplied by the fluid flow rate $Q$ into the expanding bellows volume. Figure 5a shows that the liquid flow rate $Q$ is to some degree responsive to pressure drop sustained by passage of the liquid through the inlet duct, even if the linear actuator is designed to provide a constant displacement rate of the movable end of the bellows. By the time $T_3$, $Q$ is essentially constant until the expansion is stopped at time $T_1$. Figure 5b shows the bellows current $i$ as measured by a low impedance electrometer so that Equation (4) is valid. The charge density is then determined by simply dividing the measured current $i$ by the flow rate $Q$ during the time interval $T_3$ to $T_1$ when both $i$ and $Q$ are constant. Note that the area under the curve in Figure 5b is not the same during the expulsion interval, $T_1$ to $T_2$, as during the sampling period. This illustrates the charging within the ACS due to the relative motion between the fluid, the inner probe tube and the bellows.

Alternatively, the voltage between the shield and conductive container is measured with a sufficiently high impedance circuit so that the current to the circuit remains essentially zero. Integrating Equation (1) and using the resistive terminal constraint, $v = iR$, the voltage that develops as charge entrained in the fluid enters the conductive container is

$$v(t) = \frac{1}{C} \int_0^t \rho Q dt' + \frac{1}{RC} \int_0^t v(t') dt' + v(0) \quad (5)$$

By using an electrometer of sufficiently high impedance such that the time constant $RC$ is much greater than the sampling period, the second term on the right of Equation (5) is negligible. The time dependent voltage is simply the instantaneous total net charge within the bellows divided by the capacitance between the shield and conductive container plus the initial voltage at the start of the measurement. To force $v(0) = 0$, this voltage mode, requires shorting the terminals prior to each measurement because the convection currents during the filling and discharge cycles are asymmetric. This asymmetry, due to flow electrification charge separation within the ACS is illustrated in Figure 5c. On the inlet cycle when the charge density is measured, additional charge is also separated by the flow within the inner probe conduit and bellows volume but since this charge is balanced by the image charge left on the wall, there is no additional contribution to the measurement. However, on the discharge cycle when the oil is displaced out of the ACS, even though there is no charge density measurement, a different amount of charge is expelled than entered including that due to charge separation within the ACS during intake and discharge. This results in a different voltage at the end of discharge than at the start of the cycle. If the oil is highly insulating so that the dielectric relaxation time is long compared to the fluid residence time within the ACS, the amount of charge expelled exceeds the amount of charge brought in by the amount of charge separated within the ACS both on inlet and discharge intervals. If the dielectric relaxation time is very short compared to the fluid residence time, all of the charge within the ACS, both due to entrained charge brought in and charge separated on the conductive container inner wall on inlet will relax towards zero. In the experiments reported here the dominant contribution to discharge current is then due to charge separation within the ACS during the discharge interval.

If the terminals were not shorted, the voltage magnitude would undergo a net increase each cycle to a value which would exceed the range of the electrometer. Current-mode operation, is preferred because measurements deduced in the voltage mode, depend on capacitance $C$ more significantly than do measurements in the current mode and although steps have been taken to reduce the change in $C$ as the bellows expands, complete elimination of time variations in the capacitance is not possible.

### 3.3 REPRESENTATIVE MEASUREMENTS USING THE CC

#### 3.3.1 ACS MEASUREMENT CYCLE

The Couette Charging apparatus of coaxial cylinders in Figure 6 rotates the inner cylinder at speeds up to 2000 rpm. The cylinder walls on either side of the annular oil gap can be bare metal or covered with cylindrical insulating paper or polymer sheets. The charge density in the liquid is controlled by the rotational speed of the inner cylinder and by the magnitude and frequency of the applied voltage [13, 14, 17–19].

Figure 7 shows records of the measured current, as in Figure 5b, from a low impedance electrometer (current mode) connected to the ACS. A 3.18 mm diameter straight probe, with the inner conduit of diameter 1.8 mm recessed 2 mm, was inserted through the outer aluminum cylinder with the tip of the probe flush with the inner wall of the outer cylinder. Figure 7a was the response as a function of time with the rotational speed varied and with an applied ac peak voltage of 4 kV at 1 Hz between the bare aluminum cylinders of the CC. With the inner cylinder stationary (0 rpm), there was no charge within the fluid and no current was recorded as fluid was...
drawn into the bellows volume. However, as previously discussed, positive charge separation within the ACS results in a negative current when the fluid is expelled. This part of the current waveform is not relevant to the measurement. Digitally automated, the measurement is taken only when fluid is being drawn into the bellows volume. With the inner cylinder rotated at 500, 1000, 1500, and 2000 rpm, the positive current due to positive charge in the oil increased with rotational speed. Since the dielectric relaxation time of the oil was about 16 s, which was much less than the approximate 1 min measurement cycle for the ACS, charge separated within the ACS during the discharge interval primarily contributed to the discharge current. Thus in Figure 7 even though charge brought into the ACS increased with increasing inner cylinder rotation rate, the discharge current remained approximately unchanged.

The ACS was controlled with a data acquisition/control system and an electrometer was used to measure the current between the bellows and shield. The following measurement procedure was programmed. With the bellows held stationary, the current was averaged from the time \( T_0 \) until the time \( T_1 \) (Figure 7a) in order to account for any measured current without charged fluid brought into the Faraday cage. Such signals are due to the zero reference drift of the electrometer, charge separation at the probe tip due to the moving fluid, and capacitive coupling to external electric fields. This offset was negligible for most measurements, but was an important correction for small charge densities. From the time \( T_1 \) until the time \( T_3 \), the bellows end was expanded at a constant displacement rate of 0.254 mm/s. Because the bellows volume was not completely rigid and thus was to some degree responsive to pressure drop sustained by passage of the fluid through the inlet duct, even though the end of the bellows moved with constant velocity, the time dependence of the volume rate of flow was an approximately exponential function that was essentially constant by the time \( T_2 \). With an effective area of 7.1 cm² for the movable end of the bellows, the steady state flow rate was 0.18 cm³/s. The charge density was calculated from the average value of the current between the times \( T_2 \) and \( T_3 \). The value of the zero reference current was subtracted from the average current and that difference divided by the steady state flow rate. By averaging the signal from the slight ac coupling to the electric field between the cylinders over an integer number of cycles, slight ac variations are filtered out of the measurement. The measurement cycle was completed by reversing the direction of the linear actuator to discharge the fluid to the charge trap which was
a charge relaxation region as shown in Figure 6. The trap had a volume of $1.85 \times 10^{-3} \text{ m}^3$ and with a flow of 0.18 ml/s, the residence time was $\tau_{\text{trap}} = 10^4 \text{ s}$ which is $\approx 600$ times longer than the dielectric relaxation time $\tau_e = 16 \text{ s}$ so that the oil charge leaving the trap to enter the CC had relaxed sufficiently. The charge trap is not necessary if sufficient time exists between samples so that charge exiting the CC relaxes before the next measurement.

Figure 7 shows the smaller currents with no applied voltage between the cylinders. Note that for each complete cycle, the area under the curve was not the same during the filling and discharge intervals. This again illustrates the fact that as the fluid was drawn into the bellows and then expelled, electrification processes on discharge indeed resulted in an entrained charge from internal charging due to the relative motion between the fluid and the CC conductive container. When the fluid was returned it had a greater charge density than that sampled, but because the measurement was made during the filling interval, the expelling of this charge during the discharge interval had no influence on the measurement. Because the fluid was charged as it left the CC and the sampling rate was fast as compared to the dielectric relaxation time, the fluid was returned to a relaxation region to avoid measuring this self separated charge density during the following cycle. If the measurement was made in a duct, the discharge line could have been placed at a downstream location.

3.3.2 VERIFICATION OF ABSOLUTE CHARGE SENSING

To verify that the ACS did indeed accurately measure the net charge density entrained in a liquid, simultaneous measurements of the charge density entrained in Gulf Transcrest H transformer oil between the cylinders of the CC were made with the ACS and a continuous flow sampling system shown in Figure 1 [13, 14, 16, 17]. In the continuous flow measurement, pressure in the fluid reservoir forces the oil through a relaxation chamber (charge trap) so that charge entering the CC is negligibly small. The fluid is charged by the rotation of the inner cylinder and by injection due to applied ac HV. The charged fluid exits the CC through a shielded metal pipe electrically connected to the receiver tank but insulated from the outer cylinder of the CC by a short length of insulating tube. As charged fluid flows out of the CC into the metal pipe, the convection current is measured by the electrometer connecting the receiver to ground. Providing that charging effects in the insulating tube are negligible, the electrometer current is the product of the CC oil charge density and volume rate of flow.

Both samples of the oil were taken at the top of the charging apparatus but on opposite sides. A flow rate of $1.52 \text{ cm}^3/\text{s}$ was used for the continuous flow system which allowed an experimental run time of 31 min before the oil in the receiver had to be transferred back into the reservoir. The total entrained charge densities consisting of charge separation by flow and charge injection from applied HV were measured simultaneously by the ACS and electrometer connected to the receiver as functions of rotational speed and applied ac voltage amplitude and frequency with typical results shown in Figure 8.

Total entrained charge densities measured at the top of the CC apparatus, (a) due to charge separated by flow and (b) due to charge separation by flow and charge injection by applied HV, measured simultaneously with the ACS (open symbols) and continuous sampling flow system (filled symbols) as a function of inner cylinder rotational speed.

On the average, the data from the ACS was at most 1.7% greater than the continuous flow sampling system. The maximum sensitivity of the continuous flow measurements were limited by the detection electronics to be 1
μC/m³ but could be improved with more sensitive electronics or by using a greater sampling volume rate of flow.

### 3.3.3 PRELIMINARY MEASUREMENTS IN THE FIELD

Due to its small size and the attribute of no net accumulation of fluid while running continuously, the ACS is suitable for field monitoring of power transformers or as a laboratory bench instrument. To this end, the ACS was used for preliminary field measurements of electrification charging of transformer oil in pipe flow driven by a pump [9]. The ACS was connected to a flange just after the discharge side of a 6 HP pump in a flow loop containing 7600 l of oil.

Although not shown in Figure 2, two springs were used to compensate for the weight of this oil from the ≈ 4 m high oil reservoir which gives ≈ 35 kPa of pressure head. These springs were attached between the grounded movable metal plate and the front of the ACS case where the sampling probe connects. The high pressure is not a problem during the intake of fluid as the pressure acts in the direction to help expand the bellows volume. The problem arises in returning the fluid to the system as the stepper motor was not strong enough to push the fluid back against the large static head and pressure rise from the pump. The springs increased the measured maximum operating pressure from 17.5 to 77 kPa.

With the pump off so that the oil was stationary, no charge was detected by the ACS. With the pump turned on, the measured average charge density in the oil for flow rates of 2400 to 4100 l/min decreased from 10.6 to 5.0 μC/m³. The charge density decrease with increasing flow rate was probably because the flow was decreased by a downstream valve keeping the pump impeller tip speed constant. By increasing the flow rate, the charge generated per unit time by the pump was mixed with a larger volume of fluid resulting in a reduced charge density. This is because the oil residence time in the pump is much shorter than the dielectric relaxation time and diffusion time. Typical values for oil are dielectric relaxation time ≈ 16 s while the diffusion time is typically of order 1000 s. For a pump at 3 m³/min with a volume of about 4 l, the residence time is ≈ 1.25 ms. With a constant impeller speed so that the diffusion sub-layer thickness remains constant, the charge density exiting the pump is inversely proportional to flow rate. Such behavior was previously demonstrated for continuous flow measurements in the Couette Charger system [13, 14].

### 3.4 FIELD DEPLOYABLE ACS

#### 3.4.1 IMPROVEMENTS OVER LABORATORY ACS

A portable computerized version of the ACS has also been developed which incorporates the required sensitive electronics and signal conditioning procedures into a compact unit which may be installed in field locations as illustrated in Figure 9.

![Diagram of the improved portable ACS.](image)

Diagram of the improved portable ACS. The inner conductor of the sampling probe connects to the inlet of the electrically actuated valve and the outer conductor connects to the grounded case.

This version uses an electrically controlled 2-way valve which can be energized to discharge the fluid to a downstream location or relaxation region. If the valve is not energized during the discharge, the fluid is expelled from the ACS through the sampling probe. Since the fluid exiting the ACS is charged, the next measurement must then be delayed long enough for the fluid to relax or wash away. The valve is energized with an ac voltage to minimize surface charge buildup on its insulating parts. With a dc energized valve, leakage of surface charge through the ACS was found to erroneously contribute to the charge density.
measurement. The valve also replaces springs when the fluid pressure exceeds the capability of the stepper motor. There is no problem on inlet as the fluid pressure acts to help the stepper motor expand the bellows. The problem arises on discharge as the stepper motor reverses and tries to compress the bellows and return the fluid. If the pressure is too great the stepper motor stalls. The valve can then be enabled to discharge the fluid to a low pressure region. To further increase the maximum operating pressure, a compression type spring can be placed between the movable grounded disk and stepper motor.

The controller digitally keeps track of the bellows position by counting the number of steps clocked to the stepper motor whereas the analog laboratory version used a 10 turn potentiometer connected to the motor to measure position. The field version has its own current preamplifier built in so that an external electrometer to measure the current between the bellows and the grounded shield is no longer needed. An optical sensor is used to always start the bellows at the same initial position and a purge bellows command squeezes the bellows as tightly as possible to remove any trapped air.

The field deployable ACS operates in conjunction with a microprocessor based control box. The system has been designed for both laboratory use and unattended logging of remote field data. Communication with the control box is via an RS-232 interface using speeds up to 9600 baud or over a telephone line with a 300 baud integral modem. Commands are simple, short, and structured for use with external computer programs or for manual operation from a computer or terminal. Measurements can be started either manually or automatically at regular intervals. The data is stored in a 32K RAM buffer in the control box and may be read out at the user's convenience. Parameters which control the sampling flow rate, sampling times, and enable the valve on the discharge of fluid may be changed from the terminal and are stored in non-volatile memory in case of power failure. Also included is a battery-backed-up real-time clock to date and time stamp all measurements. The same measurement procedure described in Section 3.3.1 has been implemented in the control box software.

3.4.2 ACS CALIBRATION

The field deployable ACS uses a current preamplifier with a 10 GΩ feedback resistor to measure the current from the bellows to ground. The control box for the ACS has a user specified current calibration constant which is the ratio of the exact value of this feedback resistor to its nominal value of 10 GΩ. The value of this resistance was measured by connecting a 1.5 volt dry cell in series with the ≈ 10 GΩ resistor for a current of ≈ 150 pA. The output voltage of the preamplifier was measured and the exact source current was measured with a well calibrated electrometer. Calibration of 14 ACS units gave a range of 0.964 to 0.999 for the current calibration constant.

The mechanical properties of each ACS also slightly vary from unit to unit. The volume of liquid displaced after a sample of liquid was drawn into the bellows was measured with a 10 ml graduated cylinder. The charge calibration constant is calculated by the relation

\[
\text{charge calibration constant} = 1000 \frac{\text{displacement}}{\text{volume}} \quad (6)
\]

where the displacement is the linear distance the bellows moved when it sampled the measured volume of fluid. Calibration of fourteen units gave a range of values from 61.24 to 61.67.

The charge calibration constant is used by the control unit to calculate the charge density \( \rho (\mu C/m^2) \) from the step rate of the motor in Hertz, the measured offset current \( i_{\text{offset}} \) (pA) and the measured signal current \( i_{\text{signal}} \) (pA) by

\[
\rho = \frac{(i_{\text{signal}} - i_{\text{offset}})(\text{charge calibration constant})}{\text{motor step rate}} \quad (7)
\]

The instrument records the average measured offset current in pA, the average measured signal current in pA, the computed charge density from Equation (7) in \( \mu C/m^2 \), the current gain scale factor, the overload count of the number of current signal samples which exceeded the maximum magnitude of the A/D converter, and the date and time of the measurements. With auto-scaling enabled, the scale factor is adjusted up or down between measurements to ensure that the current measurements are within the optimum range without overload.

Simultaneous measurements of the charge density were made using the Couette Charger with the laboratory and two field versions of the ACS to test that each gave the same value of charge density [17]. The probe from each ACS was radially and symmetrically inserted into a metal pipe that was connected to the output of the CC. A continuous flow of oil at a rate of 10 ml/s was imposed by a pump to pass oil through the pipe and back to the CC inlet. With the terminals of the CC short circuited and

\[
\frac{M}{10} = 1000 \frac{\text{displacement}}{\text{volume}} \quad (6)
\]
inner cylinder rotating at 2000 rpm all three ACS’s gave charge density values within 6% of each other. With the higher charge density using an ac voltage of 4 kV peak at 0.5 Hz, all three ACS’s agreed within 2%.

3.5 LABORATORY TESTING USING A CLOSED PUMP DRIVEN FLOW LOOP

3.5.1 EXPERIMENTAL CONFIGURATION

To further test the field ACS’s in a more robust environment, a closed flow loop shown in Figure 10 was constructed where a pump drives transformer oil through standard iron piping of 3.75 cm inner diameter connected to a large volume reservoir (220 l oil drum) electrically isolated from the grounded piping by PVC tubing. The system includes a parallel flow loop which is electrically isolated by nylon fittings and contains a paper oil filter which can be valved in or out through valves 2 and 3, a gate valve (valve 1) to control the flow rate through the main flow path, and a flow meter to monitor the total volume flow rate. The flow speed could also be independently controlled by varying the pump impeller speed from the ac motor controller. The paper oil filter was used as a source of electrification charge that could be controlled by appropriate setting of valves 2 and 3. If all the flow was directed through the filter by fully closing valve 1 and fully opening valves 2 and 3 the maximum flow rate was 70 l/min and the volume charge density was of order 100 to 500 pC/m³ depending on oil temperature over the range of 65 to 100°F. If none of the flow passed through the filter by fully opening valve 1 and fully closing valves 2 and 3 the maximum flow rate is 100 l/min and the volume charge density is of order 4 to 10 pC/m³. The ACS measured charge density with the pump off, so that the pipe flow is zero, is of order 1 μC/m³. This small charge density was due to charging at the probe tip as the fluid was drawn into the Faraday cage. Thus, without the paper filter, ACS measured charge densities need to be corrected by subtracting the zero flow charge density. With the paper filter, this zero flow correction is negligible.

The oil used in preliminary measurements reported here had a moisture content of 38 ppm and an ohmic conductivity of σ = 1.8 × 10⁻¹² S/m. The system was entirely filled with oil to minimize air content and thereby avoid complications of bubbles. The inlet pipe to the reservoir extended to the end of the oil drum so that entering charged oil would spend an entire residence time of \( \tau_r = V/Q \) in the drum of \( V \approx 220 \) l at flow rate \( Q \) up to 100 l/min before exiting. The oil dielectric relaxation time is then \( \tau_r \approx 11 \text{ s} \) while the minimum residence time at 100 l/min is \( \tau_r \approx 127 \text{ s} \).

An electrometer in current mode was connected to the reservoir oil barrel. A low pass electronic filter on the electrometer input was necessary to reduce ac electrical noise that could saturate the electrometer. The measured electrometer current was about 100 to 500 nA with all the flow going through the filter (valve 1 fully closed, valves 2 and 3 fully open) and about 2 to 5 nA with none of the flow through the filter (valve 1 fully open, valves 2 and 3 fully closed). The magnitude of the measured current should equal the difference between convection currents entering and leaving the oil barrel. Using the conversion factor that 3.8 l/min = 63.1x10⁻⁶ m³/s, the maximum flow rate of 100 l/min corresponds to \( Q = 1.64 \times 10^{-3} \text{ m}^3/\text{s} \). With the pipe cross-section area of \( A = 1.14 \times 10^{-3} \text{ m}^2 \) the average flow velocity is \( U = Q/A = 1.44 \text{ m/s} \). With a pipe diameter of \( D = 0.0381 \text{ in} \) and representative room temperature oil kinematic vis-
The electrometer current from the oil drum should equal the difference in convection currents entering (measured by ACS#1) and leaving (measured by ACS#2) the oil drum. The ACS measured charge densities at the inlet, \( \rho_{in} \), and outlet, \( \rho_{out} \), of the oil drum with flow rate \( Q \) give the difference in convection currents, \( i_{acs} \), as

\[
i_{acs} = (\rho_{in} - \rho_{out} - \Delta \rho_0)Q
\]

(8)

where \( \Delta \rho_0 \) is the zero flow correction due to the slight charging at the probe tip when the pump is turned off so there is no flow in the pipe

\[
\Delta \rho_0 = (\rho_{in} - \rho_{out})|_{Q=0}
\]

(9)

The zero flow correction, \( \Delta \rho_0 \), is negligible for the large charge densities when the flow passes through the paper filter, but is important for low charge density measurements when the flow does not pass through the paper filter.

From conservation of charge, the difference in convection currents should equal the total circuit current flowing from the drum through the electrometer to ground

\[
i_{acs} = i_E
\]

(10)

Charge densities were measured at the inlet and outlet of the isolated oil drum, grounded through an electrometer recording current \( i_E \). Both ACS probe tips were at the center of the pipe and the stepper motor was set at 10 steps per s. It was found that after the pump was turned on that the system temperature would gradually rise taking about 12 h to reach a steady state temperature of \( \approx 38^\circ \text{C} \) from the ambient temperature of \( \approx 18^\circ \text{C} \). The temperature dependent oil charge density, \( \rho_{in} \), at the tank inlet started at \( \approx 120 \mu \text{C/m}^3 \) and reached a maximum value of about 475 \( \mu \text{C/m}^3 \). The relaxed charge density, \( \rho_{out} \), at the tank exit was much smaller varying from \( \approx 6 \) to \( 17 \mu \text{C/m}^3 \). The electrometer current started at 111 nA at \( 18^\circ \text{C} \) and increased to 476 nA at \( 38^\circ \text{C} \).

Even though the system temperature was changing with time, with negligible zero flow correction factor, \( \Delta \rho_0 \), the difference in convection currents to and from the tank, \( i_{acs} = (\rho_{in} - \rho_{out})Q \), should instantaneously equal the measured electrometer current \( i_E \). The values of \( i_{acs} \) and \( i_E \) tracked together and were within roughly 10% of each other. Straight probes and probes with right angle bends as in Figure 2 gave the same results. Measurements made with various probe lengths from 15 cm to 2 m also gave the same charge density measurements although with the 2 m long probe, the stepper motor rate had to be decreased to five steps p/s so that the pressure drop through the probe did not exceed the maximum force capability of the stepper motor.

Without the paper filter in the flow loop (valves 2 and 3 fully closed, valve 1 fully opened), the charge density in the oil volume was due to charge separated from the pipe walls and from within the pump. Because this charge density was so small, it was difficult to obtain a good current balance in agreement with (10) because small, non-controllable temperature dependent contributions from the probe tips and insulating PVC tubing that isolates the drum in Figure 10 were significant. With low charge densities, the zero flow correction, \( \Delta \rho_0 \), in Equation (9) is important. Similar charge density measurements on either side of the paper filter using ACS#'s 3 and 4 in Figure 10 have convection currents that balance the measured electrometer current connected to the filter housing. The difference in convection currents through the filter agreed well with the measured electrometer current.

### 3.5.2 Charge Density Distribution

In computing the convection currents, we measured the charge densities at the pipe center and assumed that the charge density was uniform across the pipe cross-sectional area. To check the spatial uniformity of the charge density at the tank inlet, ACS#1 probe tip was moved across the pipe diameter for high \( \approx 70 \text{l/min} \) and low \( \approx 20 \text{l/min} \) flowrates. The measured charge density at each position is listed in Table 1 with all the flow directed through the paper filter (valve 1 fully closed, valves 2 and 3 fully open). The ACS probe tip at the tank exit, ACS#2, was kept at the pipe center. The radius weighted average charge density over the drum inlet pipe cross section is approximately 6% lower than the charge density at the center of the pipe. The average difference in convection currents, \( i_{acs} \), can thus be approximately computed by multiplying the measured charge density at the center of the pipe by 0.94 thus making the net value of \( i_{acs} \) closer to \( i_E \) listed in Table 1. Thus at 20 and 70
l/min, the measured values of $i_{acc}$ at the pipe center 1.9 cm in Table 1 of 59.6 and 483.2 nA, when corrected by multiplying by 0.94 yields values of 56 and 454 nA which are much closer to the measured electrometer current values of 51 and 450 nA. For all subsequent measurements the probe ends were placed at the center of the 3.81 cm diameter pipe.

Table 1.
ACS measured charge densities at the inlet to the reservoir (oil drum) as a function of the probe distance $z$ from the far pipe wall for turbulent ($\approx 70$ l/min, upper values) and laminar ($\approx 20$ l/min, lower values) flows through the paper filter (valve 1 fully closed, valves 2 and 3 fully open). The ACS probe at the drum outlet was kept fixed at the center of the pipe ($z \approx 18.7$ mm). The oil temperature at 70 to 72 l/min was $\approx 33$°C and at 20 to 21 l/min was $\approx 20$°C. The measured charge densities with zero flow were $\rho_{in} = 0.55 \mu C/m^3$ and $\rho_{out} = 2.32 \mu C/m^3$ so that $\Delta \rho = -1.77 \mu C/m^3$ is negligible.

<table>
<thead>
<tr>
<th>Position (mm)</th>
<th>$\rho_{in} = \rho_1$ ($\mu C/m^3$)</th>
<th>$\rho_{out} = \rho_2$ ($\mu C/m^3$)</th>
<th>$i_{acc} = (\rho_{in} - \rho_{out})Q$ (nA)</th>
<th>$i_g$ (nA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>411.4</td>
<td>15.79</td>
<td>446.8</td>
<td>450</td>
</tr>
<tr>
<td>1.17</td>
<td>419.1</td>
<td>15.79</td>
<td>455.5</td>
<td>450</td>
</tr>
<tr>
<td>3.17</td>
<td>425.0</td>
<td>16.43</td>
<td>461.4</td>
<td>450</td>
</tr>
<tr>
<td>6.35</td>
<td>414.0</td>
<td>17.77</td>
<td>454.5</td>
<td>450</td>
</tr>
<tr>
<td>9.52</td>
<td>430.8</td>
<td>14.56</td>
<td>472.7</td>
<td>450</td>
</tr>
<tr>
<td>11.27</td>
<td>436.4</td>
<td>15.21</td>
<td>478.3</td>
<td>450</td>
</tr>
<tr>
<td>15.9</td>
<td>441.7</td>
<td>15.59</td>
<td>481.2</td>
<td>450</td>
</tr>
<tr>
<td>17.41</td>
<td>446.7</td>
<td>15.74</td>
<td>487.8</td>
<td>450</td>
</tr>
<tr>
<td>19.0</td>
<td>443.6</td>
<td>15.91</td>
<td>493.2</td>
<td>450</td>
</tr>
<tr>
<td>22.2</td>
<td>445.8</td>
<td>16.43</td>
<td>484.8</td>
<td>450</td>
</tr>
<tr>
<td>26.4</td>
<td>450.8</td>
<td>17.37</td>
<td>468.2</td>
<td>450</td>
</tr>
<tr>
<td>28.6</td>
<td>436.0</td>
<td>15.73</td>
<td>477.3</td>
<td>448</td>
</tr>
<tr>
<td>31.8</td>
<td>422.6</td>
<td>16.10</td>
<td>461.8</td>
<td>448</td>
</tr>
<tr>
<td>34.9</td>
<td>421.7</td>
<td>15.11</td>
<td>461.7</td>
<td>448</td>
</tr>
<tr>
<td>38.1</td>
<td>406.0</td>
<td>14.8</td>
<td>439.3</td>
<td>450</td>
</tr>
</tbody>
</table>

Because the residence time, $\tau_r = V/Q$, in the 220 l drum, of order 3 min at 70 l/min, is much longer than the dielectric relaxation time of the oil, $\tau_e \approx 11$ s, the entering charge has greatly decayed before exiting the oil drum. If there is negligible charge separation within the tank because the mean flow velocity within the tank is greatly reduced from that in the pipes, and since residence and diffusion times are much longer than the dielectric relaxation time, the exiting charge density is related to the inlet charge density as [13,14]

$$\frac{\rho_{out}}{\rho_{in}} \approx \frac{1}{1 + \tau_r/\tau_e} \approx \frac{\tau_r}{\tau_e}$$

(11)

At 70 l/min through the 220 l oil drum, the residence time is $\approx 183$ s so that the ratio of exiting to inlet charge density should be $\rho_{out}/\rho_{in} \approx 0.06$.

Future measurements will use this flowloop to gain experience in the measurement of electrification charging with and without the paper filter as a function of temperature, flow rate, oil moisture, oil conductivity, and concentrations of trace impurities.

4. EXTENDED MEASUREMENT APPROACHES

The primary operating mode of the ACS is to directly sample charged fluid from a moving flow. However, various types of test sections can be placed just before the probe tip to directly measure electrification from different fluid/solid combinations.

4.1 PAPER PROBE MEASUREMENTS

Early work using the Couette Charger apparatus with continuous flow of transformer oil with paper covered cylinders had difficulties of irreproducible measurements including charge polarity reversal just after a system was first assembled [13,14]. Initially the charge density in the oil was negative, gradually becoming positive over a 7 day period. During this interval, the results were seemingly not reproducible. To accelerate the time to reach reproducible results, Lyon dried his paper/oil system by heating it to 90°C for 16 h under a vacuum, following the drying procedure used with commercial transformers. The results were then immediately consistent from run to run with positive charge density in the oil.

Using the ACS with a step change in temperature in a thermally controlled Couette Charger facility, measurements have shown the strong dependence of the charge density in the moving oil on temperature and moisture level in the oil and paper including polarity reversal [17, 19]. Because the moisture levels in an oil/paper system are strong functions of temperature it is difficult to separate the effects of moisture from that of temperature. To overcome this difficulty a thin tube of rolled paper was...
placed within a grounded metal tube. The assembly was
directly connected ahead of the ACS probe. With the sys-

tem maintained at a constant temperature of 22°C moist
oil of 53 ppm moisture from a beaker was drawn through
the paper probe into the ACS at 0.18 ml/s and the charge
density was measured as a function of time as shown in
Figure 11. The cylinder of inner radius 1 mm and outer
radius 1.5 mm was formed by rolling 7 layers of Manning
220 paper which was taken off a shelf where the relative
humidity was 60% and placing it inside a grounded metal
tube. Oil was drawn from a beaker through the shielded
hollow paper cylinder into the ACS. A 1 min sample was
taken every 30 min with no flow in between. The results
show that as in Lyons’ work [13,14], the charge density
had a negative value to start with and attained an
as-
ymptotic positive value after about 5 h. This transient
is believed to be due to moisture and/or trace materials
in the oil and paper coming into equilibrium. Additional
experiments are needed in which the paper moisture is
controlled to test this hypothesis and existing streaming
current models for electrically developing ducts need to
be adapted so that comparison can be made with other
measurements. By contrast with other CC measurements
with step changes in temperature [17,19], the origins of
the equilibration in Figure 11 are not thermal.

4.2 FLOW THROUGH A FILTER

The ministatic tester earlier described in Section 2.1
measures the electrical charging tendency of oil forced
through a cellulose filter. Generally the measurement
procedure only passes the oil once through the filter, so
that the oil and filter paper do not have time to reach
moisture and/or trace material equilibrium. Continuous
measurements can be easily achieved by placing the fil-
ter assembly at the entrance of the ACS probe as shown
in Figure 12 with the flow drawn and expelled by the
ACS instrument with expansion and contraction of the
bells. Single pass measurements through a filter on a
number of transformer oils and gasoline were performed
with the ACS with charge density values similar to those
measured using the ministatic tester. Continuing work
will have continuous flow of the same oil through the fil-
ter so that the oil and filter paper can reach equilibrium.

4.3 MEASUREMENT SENSITIVITY

For our transformer oil measurements, a typical offset
current value is of order 0.1 pA. If the bellows is driven
at the usual 10 steps per s, corresponding to a flow rate
of 0.18 ml/s, a measured bellows current of 1 pA corre-

sponds to a fluid charge density of about 5 μC/m³. It is of
interest to see if the ACS can also be used for atmospheric
electricity measurements. During fair weather there are
less than 10⁹ elementary charges per cubic meter corre-

sponding to about 0.16 nC/m³. If the stepper motor rate
is increased to 100 steps per s, the ACS current for this
charge density is then 0.29 fA.
To measure such a small signal, all sources of signal noise need to be greatly reduced. For our present design, even if the stepper motor is stationary and sampling uncharged air there is typically about a 12 fA current due to leakage current through the amplifier. This current is stable so that the charge density varies at most by $\pm 0.01 \mu C/m^3$ over a 40 h period allowing compensation for this residual background current. As the bellows expands the current changes up to 50 fA, probably due to the last term on the right of Equation (1) where the charge on the surface of the ACS changes with time due to changes in ACS voltage and capacitance with respect to nearby circuit components as given by the last two terms on the right of Equation (3). This base-line signal can be reduced with better shielding around the bellows so that the voltage difference between Faraday cage and nearby circuit components is minimized. There is also some noise about the signal due to a periodicity of four from the 4 stator windings that drive the stepper motor and a periodicity of 48 from the 48 poles on the stepper motor rotor as shown in Figure 13. With a four point averaging the signal is greatly smoothed but still has a periodic variation. A 48 point averaging as used in our current ACS's removes the remaining variations resulting in a completely smooth signal shape shown in Figure 13. It appears that the ACS sensitivity can be improved for charge density measurements by minimizing the electronic drifts and offsets, holding the ACS Faraday cage closer to ground potential, minimizing changes in capacitance as the bellows moves, increasing shielding between the Faraday cage and nearby components, increasing the motor step rate and bellows volume, and improving the ACS signal processing algorithms.

5. CONCLUDING REMARKS

Flow electrification charge density measurements can be made using the Absolute Charge Sensor by bringing a sample of charged fluid into a Faraday cage with no extraneous contributions from charge separated within the ACS itself and independent of the fluid electrical properties and velocity. For flow electrification measurements in transformer oils and gasoline, typical values of the lowest measurable charge density is a few $\mu C/m^3$. The typical ACS stepper motor moving at 10 steps per s corresponds to a volume rate of 0.18 ml/s so that the lowest measurable current to the ACS is then of order 180 fA. Present limitations at low charge densities concern a correction factor due to charging at the probe tip and nearby surfaces which seems to be temperature dependent. However, this correction is generally negligible for most electrification processes which lead to charge densities greater than 10 $\mu C/m^3$. To further reduce probe charging, other polymers besides Teflon are being tested to find the insulating sleeve material that is least charging.

The ACS is being used in research to quantify magnitude and polarity of static charge generation and relaxation within gasoline fuel pumps and filters and in representative forced oil cooled components of a power transformer as a function of oil temperature, moisture, gas content, flow rate and concentration of trace impurities. Electrification measurements are planned in a large flow loop like that discussed in Section 3.5 consisting of various pumps, valves, heat exchangers, pipe sections, oil storage tank, and coil sections used in typical power transformers, each electrically isolated and grounded through a low impedance electrometer in current mode. Multiple ACS's throughout the flow loop will measure the charge density entering and leaving each component as well as the total circuit current through the electrometer to ground in order to identify which components and factors may be
responsible for transformer failures due to flow electrification.

Another activity is also planning to place an ACS at the top of an operating transformer to continuously monitor the oil charge density. With the ACS it is planned to continuously research electrification mechanisms in true application environments.

ACKNOWLEDGMENT

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IN MEMORIAM

James R. Melcher, aged 54, an engineer and scientist widely respected for his practical applications of continuum electromechanics and a member of the M.I.T. Department of Electrical Engineering and Computer Science since 1962, died on 5 January 1991. Despite his illness, the last six months of his life were remarkably productive. He worked closely with his coauthors on the preparation of this paper.