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Review of the I.U.T.A.M.–I.U.P.A.P. Symposium on Electrohydrodynamics

By J. R. MELCHER
Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

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A Symposium on Electrohydrodynamics sponsored by the International Unions of Theoretical and Applied Mechanics and of Pure and Applied Physics was convened at the Massachusetts Institute of Technology, Cambridge, Massachusetts, from 31 March to 1–2 April 1969. Authors from eight countries presented 44 papers to an invited audience of 112. The presentations illustrated the spectrum of scientific and engineering interests in the interactions of electric fields and moving fluids. Papers were grouped in seven sessions with the following titles: Steady flows; Bulk stability and dynamics; Interfacial dynamics: Static and steady-flow equilibria; Interfacial dynamics and stability: Drops; Basic formulation; Generation and other applications; Aerosol charging and dynamics. It is expected that the majority of authors will publish their papers in the formal literature. This brief review gives only an over-view of the Symposium as seen by the author.

Preamble

In the summer of 1966, the I.U.T.A.M. asked its members to suggest topics which might benefit from a meeting of interested workers. G. I. Taylor suggested that, by contrast with magnetohydrodynamics, the area of electrohydrodynamics had been little discussed in formal meetings and deserved attention. In fact, there seemed to be no precedent for a major meeting devoted to electrohydrodynamics. The suggestion was approved, setting into motion the organization of a symposium which was to be the first co-sponsored by I.U.T.A.M. and I.U.P.A.P. The Organization and Scientific Committee consisted of: G. I. Taylor (*Chairman*), Cambridge, England; N. J. Felici, Grenoble-Gare, France; W. Fiszdon, Warsaw, Poland; C. D. Hendricks, Urbana, Illinois, U.S.A.; G. A. Lyubimov, Moscow, U.S.S.R.; J. R. Melcher (*Secretary*), Cambridge, Massachusetts, U.S.A.; and A. Walz, Berlin, Germany.

The sections which follow have the same outline as the sessions of the Symposium. A detailed listing of authors and titles of papers read at the Symposium is given in the appendix.† Our objective here is to give an impression of the directions of research that are being actively pursued, as well as some indication of where the frontiers lie.

† Asterisks will be used to indicate papers found in the appendix, rather than among the formal references.

Although the sessions tended to proceed from the scientific to the engineering aspects of electrohydrodynamics, each session was to some extent a mixture of both. Subjects of scientific interest included physiochemical hydrodynamics, liquid crystal dynamics, conduction in liquids, insulation in liquids and gases, and the fundamental aspects of macroscopic force densities. Subjects tending more toward the applied side included: boundary-layer control, power and high voltage generation, heat transfer, liquid levitation, image processing, liquid spraying, separation of biological particles, and dielectrophoretic liquid orientation.

Steady flows

The first session was opened by G. I. Taylor, who read a letter from W. T. Koiter, President of I.U.T.A.M., stating that 'it is nowadays a well-recognized phenomenon that the development of science is often most manifest in domains which overlap'. The interdisciplinary character of the Symposium was immediately apparent in the opening session. The first two papers highlighted electrohydrodynamics as seen from the traditions of physical chemistry and thermodynamics; the second two papers leaned heavily on work in magnetohydrodynamics, while the last three topics were motivated by the traditional areas of transport phenomena.

J. F. Osterle* gave the opening paper, focusing attention on field–fluid coupling in regions having dimensions on the order of the Debye length, by reviewing the area of electrolytic flows through fine capillary tubes or similar channels found in natural and artificial membranes (Osterle 1964). Research efforts were described to solve the non-linear coupling problem arising if the Poisson–Boltzmann equation is not linearized in the manner of Debye–Hückel. Further plans were mentioned to consider flows in which the general dimensions were of the order of the Debye length.

Electrophoresis and the associated zeta potential for NaCl type alkali halides in cyclohexanone, as described by W. Leiner,* continued the theme begun with the opening paper. Exterior flows around a particle supporting a double layer were considered, in contrast with the interior flows of the previous paper. Emphasis was given to careful experimental observations of the zeta potentials for a number of alkali halides, with a clear correlation of the zeta potential with the ratio of ionic radii of the alkali and the halide ions.

In a post-deadline paper, R. Cade* discussed related work in progress, aimed at developing a self-consistent electrohydrodynamic picture of the macroscopic electric potentials developed in consequence of sedimentation of particles supporting double layers: a theory of Dorn effect.

The strong influence of magnetohydrodynamics researches was apparent in the two papers presented by V. V. Gogosov on behalf of his colleagues (Gogosov *et al.** and Polyansky *et al.**). These papers represented a condensation of work on compressible (electrogasdynamic) problems (Gogosov *et al.* 1969) ranging from the basic formulation as it stems from statistical mechanics to the solution of specific flow problems. In the former category were discussions of various forms taken by Ohm's law in electrohydrodynamics, while the specific examples included compressible channel flows, such as might be of interest in energy conversion, and fields used to implement aerodynamic boundary-layer control.

It could be said that the last three papers of this session were concerned with the transport phenomena, whether it be transport of heat, of charge, or of momentum. In the experiments reported by J. E. Porter and R. Poulter,* and in a later paper by H. R. Velkoff,* flows through the annulus between a wire and a coaxial circular tube were reported. The first of these papers considered the effect of a wire-tube potential difference on the heat transfer, and especially friction factor in liquids (see Gross & Porter 1966; Coulson & Porter 1966), while the latter was concerned with changes in the friction factor found with gases (see Velkoff 1964). In both cases, it was concluded that free-charge forces were responsible. Velkoff, in particular, attributed the altered friction factor to turbulence induced in the annulus, a view consistent with the observations of others, including those in the session concerned with stability; the field-induced incipience of turbulence.

The experiments reported by R. Tobazeon* involved dielectric liquids moving at a relatively high velocity. Observations were made of the effects of fluid streaming on the distribution of space charge, using the electro-optic Kerr effect (see Croitoru 1965; Filippini *et al.* 1969).

Further comments on the effects of an electric field on convective heat transfer in annuli were given in a post-deadline paper by O. Rho, C. J. Lee and L. Trefethen.* Here, the basic mechanism of heat transfer augmentation was again the flow instability induced by a d.c. field imposed transverse to the flow direction (see Rho 1968).

Bulk stability and dynamics

The latter group of papers from the first session served to emphasize the importance of stability in understanding electrohydrodynamic flows. An analogy can be drawn with the role of stability in understanding the relationship between the laminar and turbulent flows. In contrast to instability produced by fluid convection, electrohydrodynamic equilibria are commonly unstable, even in the absence of motion. A first step in a stability study of steady electrohydrodynamic flow equilibria is the understanding of static equilibria, and hence most of the papers in this session related to the incipience of instability obtained as a layer of fluid supporting a space charge is stressed by an electric field co-linear with a space-charge gradient.

Papers in this session related to instability caused by space charge induced through one of three mechanisms. First, a single species of ions injected into the volume of a fluid across a planar boundary gives rise to a gradient in the space charge; although static equilibrium with the electric field co-linear with the space-charge gradient is possible, it is expected that the equilibrium would be unstable if

$$E\frac{dq}{dx} < 0, \tag{1}$$

where q is the space charge density and E is the electric field intensity in the x direction. Secondly, more than one species of carrier may be involved; for example, the fluid may be an essentially ohmic conductor, but by virtue of a thermal stress or initial stratification, be inhomogeneous. A gradient in electrical conductivity in a direction co-linear with the applied electric field intensity gives rise to a class of bulk instabilities, for reasons similar to those for the injection of a single species of ions. Finally, the fluid may be anisotropic in its electrical properties, in which case a fluid distortion can be accompanied by the accumulation of local space charge, with the attendant possibility of bulk instability (for background, see Avsec & Luntz 1937).

The opening paper of the second session, given by W. Helfrich,* involved interactions in the last category, the instability of nematic liquid crystal equilibria brought about by anisotropic conduction (see Heilmeier 1968). A model, which adds a body couple due to the conduction to the more conventional ones due to dielectric and diamagnetic anisotropy, is successful in explaining the 'paradoxical alignment' found at a critical voltage.

The papers by P. Atten and R. Moreau,* J. D. Blackmon and I. Catton,* and J. M. Schneider and P. K. Watson* were concerned with the prediction of instability incipience caused by the space charge due to unipolar conduction. Hence these papers dealt with the first of the three categories mentioned previously. Atten and Moreau were particularly interested in connecting their work with instabilities apparent in highly polarized fluids such as nitrobenzene with ionic impurities removed to a high degree by semipermeable membranes (see Felici, Ayant & Tobazeon 1969). They reported work concerned with establishing criteria for the incipience under particular conditions, it being recognized that the general problem has the mathematical difficulties inherent to a problem that has space-varying coefficients. Somewhat similar studies reported by Blackmon and Catton related to an attempt to solve the equations using a 'Boussinesq' type of approximation, which gave rise to an identification of the essential physical parameters. Schneider and Watson were able to give concrete results by confining theoretical attention to the case in which the ion injection occurs on the upper interface of a liquid film under space-charge-limited conditions. Their result characterizes this type of bulk instability, in that they found the critical condition for incipience of instability to be given as

$$R = 37{\cdot}3 = \frac{3\epsilon V_0}{8b\mu}, \tag{2}$$

where ϵ is the permittivity of the liquid layer, V_0 is the interface to lower electrode potential, b is the ion mobility, and μ is the viscosity. This number was termed the 'electric Rayleigh number' by the authors.

The major difficulties in theoretical treatment of bulk instabilities due to ion injection appear to lie in the area of a proof of exchange of stabilities. Even the results of Schneider and Watson depend on an assumption that this principle holds, and it is clear that further work in the area is called for, and will be forthcoming. It seems that a next topic for investigation will be the instabilities due to more than one species of carrier, as mentioned by Blackmon and Catton and, in session VII, by Hoppel and Gathman.* Also, the variational principles discussed by Atten and Moreau may develop into a powerful technique for dealing with these problems, again depending upon proof of exchange of stabilities.

P. K. Watson, J. M. Schneider, and H. R. Till* reported experiments which delineated the fundamental role of instability in steady-state and transient conduction phenomena through insulating liquid layers. In their paper, accompanying that by Schneider and Watson, they described an experiment in which a scanning electron beam was used together with suitable detection and feedback circuitry to provide space-charge-limited injection at the upper surface of the layer (see Watson & Schneider 1967; Watson & Clancy 1965). Records of the interfacial voltage as a function of time brought out the various microscopic and macroscopic phenomena involved. Among these was the onset of instability with an attendant apparent increase in the ion mobility; an onset predicted by their theoretical prediction of equation (2) to a remarkable degree of accuracy.

Watson, Schneider and Till also reported on transient conduction and convection phenomena, using a theory involving the transient of the space charge to account for the measured charging curves. Included were remarks on instabilities produced during the transient. P. E. Secker and V. Essex* also reported on transient techniques for measuring charge-carrier mobility. In their experiments, charge injection was produced by using razor blades and a grid to form an injection diode (Coe, Hughes & Secker 1966). They were led to conclude that, at sufficiently high field strengths, the effect of fluid convection on masking the true mobility could be ignored. The remarks of M. J. Gross* also related to the convection occurring after incipience of instability.

R. J. Turnbull* presented theoretical and experimental studies based upon models and fluids which could be described as ohmic. This investigation, which falls in the second category alluded to in the introduction to this section, could be regarded as concerned with instability due to more than one species of carrier. Gradients in permittivity and ohmic conductivity were taken as present either because of inhomogeneities or thermal stress (see Turnbull 1968*a*, *b*). Mainly emphasized in this work was instability caused by gradients in the polarizability of the fluid. Conditions were given for incipience of instability in the limit of no electrical conduction, but with an equilibrium space charge and gradient in electrical permittivity. A proof of exchange of stabilities was presented and detailed attention given to the limit where there is no space charge (see Turnbull & Melcher 1969). In the latter case, incipience of instability is determined by the critical parameter

$$E^2\left(\frac{d\epsilon}{dx}\right)^2 \Big/ \epsilon g\frac{d\rho}{dx}, \tag{3}$$

where ϵ is the permittivity, E the electric field intensity in the x direction, g the gravitational constant and ρ the fluid mass density. Experiments giving satisfactory agreement with theory were described. Further work relating to the effects of thermal diffusion were also described.

Interfacial dynamics: static and steady-flow equilibria

Interfaces between materials having different electrical properties form zones in which both free and polarization charges accumulate. Consequently, these are also regions in which electrical stresses are commonly found, and many of the most important electrohydrodynamic phenomena are therefore connected with fluid–field coupling at fluid interfaces. Since the time of Rayleigh, drops have been of particular interest in electric fields, if for no other reason than their obvious connexion with the electrostatics of thunderstorms. Thus, papers on the subject of interfacial electrohydrodynamics were evenly divided between those concerned with drop dynamics (session IV) and those concerned with other geometric configurations (session III), such as jets and planar layers.

In the first of these sessions, G. I. Taylor* opened with observations and thoughts about the formation of fine fluid jets streaming in a direction co-linear with an imposed electric field. It was emphasized that the remarkable tendency of the jets to remain stable and straight over much of their length under the proper conditions could be attributed to the driving shear electrical forces caused by the conduction of a small current through the jet. Observations were made on oscillations obtained when the flow parameters were in certain régimes. Analogies with the instability produced as the jet entered a fluid of high viscosity suggested the physical reason for the observed instability (see Taylor 1968). The analogy was one between the electrical shear stress in the electrohydrodynamic case, and the viscous shear in the hydrodynamic analogue. This was one of three papers in this session concerned with electrical shear forces, the others being the last in the session, and involved with interfacial instability.

There are no electrical shear stresses on the interface between fluids having highly disparate electrical conductivities. M. E. O'Neill* and D. H. Michael* considered systems of such fluids, with an analysis of the dynamics and instability of thin, non-conducting layers of insulating fluid bounded from above and below by highly conducting fluids. The effects of viscosity were included.

The electrohydrodynamics of thin films suffering viscous shear was the subject of two papers, the first by C. O. Lee and H. Y. Choi,* and the second by M. U. Kim and C. O. Lee.* In the first of these, an experiment was described in which a thin film of dielectric liquid (silicone oil) flowed down the upper surface of an inclined plane, with an electric field applied normal to the film interface (see Lee 1967). Instabilities observed on the interface had an appearance analogous to those found on the lower side of a plate in an adverse gravitational acceleration. With the interface tilted slightly from the horizontal, the instability took the form of wave crests parallel to the direction of flow. When perfectly horizontal, drops formed. Similar observations obtained with the electric field and were explained in terms of a thin film stability analysis including the effects of the Reynolds number to first order.

In the second paper on thin films, by Kim and Lee, a travelling wave of electric shear surface force was used to produce steady convection of a thin film (see Melcher & Taylor 1969). The resulting surface instability was similar to that found when streaming occurs between a gas and a liquid film. The authors described an asymptotic solution to the Orr–Sommerfeld equation, which adequately explained the experimental observation.

The stability of an insulating or semi-insulating interface stressed by a uniform normal electric field intensity was the subject of a paper by J. R. Melcher* (see Melcher & Smith 1969). Here, both normal and shear electrical stresses were important; in fact, emphasis was given to the manner in which electrical shear stresses could make a charged insulating interface behave much as a perfectly conducting interface in a normal electric stress. Theoretical developments elucidated the conditions for incipience of instability and growth rates, with effects of viscosity and finite electrical relaxation time included. Experiments were described which supported the theoretical prediction that, for fluids of viscosities found commonly in insulating liquids, the interface behaves essentially as a perfectly conducting interface (for tangential field case, see Melcher & Schwarz 1968).

The class of instabilities exemplified in the paper by D. C. Jolly and J. R. Melcher* can be regarded as the surface analogue of the bulk instabilities discussed in the earlier papers of this session. A pair of planar electrodes separated by a small insulating gap formed the bottom of a container filled with a layer of semiconducting liquid. A voltage applied between the electrodes resulted in the formation of cells in the plane of the interface (see Melcher & Taylor 1969). A theoretical model was described which successfully predicted the incipience of this instability as

$$H_e = \frac{V}{a}\left(\frac{\epsilon\epsilon_0}{\mu\sigma}\right)^{\frac{1}{2}} = 3{\cdot}28, \tag{4}$$

where V is the potential difference between the bottom electrodes, a is the depth of the liquid layer, and ϵ, μ and σ are, respectively, the liquid permittivity, viscosity and conductivity ($\epsilon_0 = 8{\cdot}85 \times 10^{-12}$). H_e has been termed the 'electric Hartmann number' as it takes the form of an analogue to the Hartmann number of magnetohydrodynamics. As the counterpart of the electric Rayleigh number, equation (2), H_e is found in dealing with systems of ohmic conductors rather than with the bulk of a single fluid subject to unipolar charging. Experiments were reported which successfully correlated theory and experiment on conditions for incipience (including voltage and wavelength) and the cell velocity after the incipience.

Interfacial dynamics and stability: drops

The first two papers in this session described experiments in which a.c. electric fields were used in first levitating, and then separating, materials where dielectrophoretic forces were dominant. In the first of these, F. Veas and M. J. Schaffer* described how dielectric liquid drops could be levitated within a second liquid of higher permittivity by means of rotating electric fields. Their approach made use of a set of three rotating fields, each having a different frequency, and non-coincident null points. Experiments were described which demonstrated the levitation, and implications for analogous magnetohydrodynamic systems discussed (Schaffer 1967).

H. A. Pohl* presented a paper on the use of dielectrophoretic forces to separate live and dead cells. Techniques were described for using non-uniform electric fields in controlling the motions of uncharged particles in the stimulating context of biological applications. He emphasized the contrast between dielectrophoresis (Pohl 1960) and the more common electrophoresis, as discussed by Leiner* in the first session. His experiments were intended to identify the site of the difference between the polarizability of living and dead cells (see also Crane & Pohl 1968). Emphasis was given to a need for a better understanding of the interplay of double-layer phenomena and dielectrophoretic effects.

In a second paper given during a post-deadline session, H. A. Pohl considered 'anomalous' motions of particles in electric field gradients; deflexions of particles in a direction opposite to what would be expected on the basis of classic dielectrophoretic forces were reported (Pohl 1968).

The next four papers were devoted to the classic subject of surface instability of perfectly conducting drops. S. B. Sample and B. Raghupathy* presented a detailed analysis of the dynamics and stability of drops, initially uncharged, and in an electric field. They used a normal mode expansion both to describe the essentially ellipsoidal equilibrium as a function of the applied electric field intensity, and to determine the frequencies of oscillation about this equilibrium. Their predicted field E_0 for instability was such that

$$E_0\left(\frac{\epsilon a}{\gamma}\right)^{\frac{1}{2}} = 0{\cdot}535, \tag{5}$$

where ϵ is the permittivity of the surrounding fluid, γ is the surface tension, and a is the radius of the drop before the field is applied, which is reasonable, in view of earlier theories (based on approximating the equilibrium as spheroidal) and experimental results that have been reported (see Taylor 1964).

Theories of drop instability and disintegration were related to meteorological applications by J. Latham,* who discussed a range of drop-field and drop–drop interactions that could be important in explaining atmospheric electricity (see Azad & Latham 1969).

T. G. Owe Berg and U. Vaughan* reported experiments in which an a.c. field was used to suspend strongly charged water droplets in the diameter range of $100\,\mu$.

The manner in which the drop disintegrates in an electric field is of great importance in applications such as meteorology, as pointed out earlier by Latham. P. R. Brazier-Smith* gave a presentation of numerical computations of the non-linear stages of drop instability in a uniform applied field. His computations gave evidence of the formation of sharp perturbances at the poles of the drop, which have been observed experimentally to lead to material ejection. A somewhat similar process of material ejection is postulated to occur in gas bubbles subject to large electrical stresses. Here, the gas is ejected from the bubble to produce what the authors, L. Chincholle and R. Coelho,* term the 'rocket effect'. The bubble is accelerated by means of its effective mass.

Evidence of the effects of viscous and electrical shear stresses on drop equilibria and stability were given by S. Torza and S. G. Mason.* The effects of electrical and mechanical fluid properties for the drops and the surrounding fluid, as well as that of the frequency of an applied a.c. field on the equilibrium shape of the drop, and the conditions for instability, were discussed. This work represents a generalization of that begun by Taylor (1966) with the authors giving clear evidence that the non-linear stages of instability (the drop break-up) depend intimately on the surrounding fluid, the relative electrical properties, hence on the shear stresses (see Allan & Mason 1962).

Basic formulation

The connexions between microscopic and macroscopic theories for the interactions of media and electromagnetic fields are often difficult to make. In electrohydrodynamics, the polarization forces (by contrast with the free charge forces) are a case in point. It is obvious from papers already reviewed that much effort will likely be given in the future to understanding the electrohydrodynamics of fluids, such as liquid crystals, wherein the appropriate macroscopic equations of motion will require new types of force densities. This session was devoted to a pair of papers given by P. A. Penfield and H. A. Haus.* In the first, a summary was given of their principle of virtual power, which leads in a structured way from information about the energy density and power flow to a determination of the continuum force density (see Penfield & Haus 1967). In the second paper, an example was considered to demonstrate the approach with a fluid consisting of a colloidal suspension of polarized particles in a neutral vehicle. The results were also applicable to magnetic fluids (Rosensweig 1966).

Generation and other applications

The emphasis in this session was on applications; propulsion and energy-conversion schemes. A dual purpose was served by the first paper, presented by S. I. Cheng.* His topic was the interaction of ions with aerodynamic flows, with the first portion of the talk devoted to debunking proposed methods for eliminating sonic boom by electrohydrodynamic techniques. He then went on to describe how electrical ion-drag forces might be used in situations where a relatively small pressure can influence the flow through a large fluid mechanical 'lever'. Examples given were that of the boundary-layer control and control of a re-entry vehicle trajectory (see also Cheng 1968). The former application was similar to one discussed by Gogosov* in the opening session. Boundary-layer control in liquids has been demonstrated by Stuetzer (1962).

A condensation-type, supersonic, electroaerodynamical, high-voltage generator was the subject of N. J. Felici.* In this approach, the object is not a highly efficient energy converter, but rather applications such as those in which a Van de Graaff generator is used. The thermodynamics of the condensation charging and energy conversion process were described, with experiments reported in which about 75 kV were produced at 12 μA in a duct 3 in. long with 0·158 in. diameter.

M. C. Gourdine* devoted his talk to describing the system specifications for an electrogasdynamic power station. In his approach, low-mobility particles are obtained by charging solid particulate entrained in the gas flow. Because efficiency was a primary consideration, relatively low gas velocities were conjectured; hence, the generator proposed had a 100 m length with an inlet diameter of 4·2 m, and outlet diameter of 8·9 m and a power density of $1{\cdot}33 \times 10^5\,\mathrm{W/m^3}$ (see Gourdine 1968).

Although the use of a charged aerosol of droplets is a recognized means of avoiding the inefficiencies introduced by ion-slip in a power converter, the generation of the charged aerosol is a key problem. A. M. Marks* discussed generation of a charged aerosol by techniques intended to avoid gross inefficiencies. Two processes for forming the charged aerosol were mentioned in his paper; one, the 'electrojet' process and the other, the 'condensation' process (see Marks 1968*a*, *b*).

In the final paper in this session, J. F. Hughes and P. E. Secker* considered a high-voltage electrostatic generator, but this time with the vehicle a liquid. Because of the relatively low mobility of ions in a liquid (in contrast to a gas), ion-slip effects could be tolerated. Experiments were reported involving a prototype generator with its characteristics compared to a simple theoretical model.

Aerosol charging and dynamics

A technology for making finely divided droplets by means of an electric field applied to the liquid conveyed through a fine capillary has become highly developed, through such applications as space propulsion. C. D. Hendricks and J. M. Crowley* presented a paper giving an over-view of studies relating to electric-field spraying of liquids as it has progressed in their laboratory over a number of years (see Hendricks *et al.* 1964). The effects of flow parameters on the specific charge and particle size were discussed and illustrated.

In a paper presented by A. Walz for P. Berenbrinck and P. Langbein,* electrical phenomena observed on the impact of water droplets at solid surfaces was described. They found intensive light flashes at the water jet impact and put forward possible explanations for the observations.

D. S. Swatik and C. D. Hendricks* carried the discussions in yet another direction by considering the production of ions at the surface of a liquid metal by 'field-induced evaporation'. Here the extremely high field intensity required to produce the effect was obtained by the field concentration associated with the sharply pointed surface of a liquid metal exposed to an applied field at the tip of a capillary. Observations were made as to how the mechanism could be used for space propulsion.

An underlying application for many of the studies of drops, droplets, and aerosols presented throughout this Symposium was possible use in meteorology. W. A. Hoppel and S. Gathman* continued a theme introduced by Latham* in the fourth session by considering the electrohydrodynamics of interacting electrified drops. Theirs was a paper concerned with the collective dynamics of two species of ions and cloud drops, with primary interest given to equilibrium distributions of charged particles and drops, and the stability thereof. Here, as in the second session, types of instability were considered which could be induced by a gradient in space charge density co-linear with a background electric-field intensity. Observations of enhanced current flow in an experiment involving radiation-induced ionization and cloud droplets were described and made a close connexion with the discussions of the session on bulk stability and dynamics (see also Hoppel 1968).

Summary

It was the original intention that this conference bring together people with a range of interests, to present and discuss original research relating to the basic electrohydrodynamic phenomena on which a spectrum of applications is based. As it turned out, the Symposium brought out applications which included the formation and coalescence of solid and liquid particles; the dielectrophoretic orientation and expulsion of liquids in zero-gravity environments; electrogasdynamic high voltage and power generation; insulation research, atmospheric and cloud physics; physiochemical hydrodynamics; including membrane flows, heat, mass and momentum transfer fluid mechanics; electro-optics of liquids and other phenomena useful for image processing, and electrofluid dynamics of biological systems.

Major emphasis was given to the 'basic' aspects of electrohydrodynamics; 'basic' meaning the quantitative description of observed phenomena. Following this approach, research confronts a succession of continually more complicated interactions. This requires that the simplest situations be understood at the outset, so that firm foundations can be established for delving into more complex ones. Thus, many of the papers in the Symposium were based on relatively simple macroscopic models, hence related to a rather confined range of fluids. As must be the case for symposia in developing areas, discussions tended to emphasize the disparity between these basic investigations and the realities of practical applications.

Felici summed up a view of many in this regard when he eloquently called for the recognition, in future work, of the complex conduction processes that occur in liquid semi-insulators.

Indeed, the challenge in electrohydrodynamic research is to make a quantitative and scientific approach to the interactions of electric fields and fluids play a significant role in the innovation of new technologies.

Appendix

The following references to papers read at the Symposium are indicated by an asterisk in the text.

Steady flows

J. F. Osterle. Thermodynamics and electrohydrodynamics of the flow of an electrolyte in a charged capillary tube.

W. Leiner. Study of zeta potentials of NaCl type alkali halides dispersed in cyclohexanone.

V. V. Gogosov, V. A. Polyansky, I. P. Semyonova and A. E. Yakubenko. Investigation into unidimensional stationary flows in electrohydrodynamics (to be published in *Izvestiya AN SSSR, Mechanika Zhidkost: i gaza*).

V. A. Polyansky, V. V. Gogosov, I. P. Semyonova and A. E. Yakubenko. Electrohydrodynamic equations and transfer coefficients in a strong electric field.

J. E. Porter and R. Poulter. Pressure drop accompanying isothermal laminar flow of a dielectric liquid through an annulus.

R. Tobazeon. Convective transfer of electric charges injected in liquid dielectrics: Study of electric fields by electro-optic Kerr effect.

H. R. Velkoff. Electrostatically-induced secondary flows in a channel.

Bulk stability and dynamics

W. Helfrich. Conduction-induced alignment of nematic crystals in electric fields.

P. Atten and R. Moreau. Hydrodynamic stability of an insulating dielectric liquid during unipolar injection (to be published in *C. r. hebd. Séanc. Acad. Sci., Paris*).

J. B. Blackmon and I. Catton. A study of the initiation of electroconvection.

M. J. Gross. Circulation induced by electric fields in insulating liquids.

J. M. Schneider and P. K. Watson. Electroconvective stability of space-charge-limited currents in dielectric liquids.

P. K. Watson and J. M. Schneider. The experimental study of electro-convection and space-charge-limited currents in insulating liquids.

P. E. Secker and V. Essex. Charge carrier mobility measurement in dielectric liquids and the role of induced liquid motion.

R. J. Turnbull. Bulk electrohydrodynamic instabilities with vertical temperature gradients.

Interfacial dynamics and stability: static and steady-flow equilibria

G. I. Taylor. The stability of a fine fluid jet in a longitudinal field (to be published in *Proc. Roy. Soc. Lond.*).

D. H. Michael and M. E. O'Neill. Electrohydrodynamic instability of a cylindrical viscous jet.

M. E. O'Neill and D. H. Michael. Electrohydrodynamic instability in plane layers of fluid.

C. O. Lee and H. Y. Choi. Electrohydrodynamic instability in laminar flow of a thin liquid layer.

M. U. Kim and C. O. Lee. Electrohydrodynamic instability of thin liquid layer in uniform shearing motion induced by a travelling potential wave.

J. R. Melcher. Electrohydrodynamic charge relaxation and interfacial perpendicular field instability.

D. C. Jolly and J. R. Melcher. Electroconvective instability in a fluid layer (to be published in *Proc. Roy. Soc. Lond.*).

Interfacial dynamics and stability; drops

F. Veas and M. J. Schaffer. Stable levitation of a dielectric liquid in a multiple frequency electric field.

H. A. Pohl. Biological dielectrophoresis: the physical separation of live and dead cells.

S. B. Sample, B. Raghupathy and C. D. Hendricks. Normal modes of oscillation of a liquid drop in an electric field.

J. Latham. The disintegration and electrification of isolated drops and drop-pairs subjected to electrical forces.

T. G. Owe Berg and U. Vaughan. Stable and unstable charged drops.

P. R. Brazier-Smith. Numerical computations of the dynamics of the disintegration of a drop situated in an electrical field (in publication, *Proc. Roy. Soc. Lond.*).

L. Chincholle and R. Coelho. Rocket effect and electrokinetic effects in dielectric liquids.

S. Torza and S. G. Mason. Deformation and burst of liquid drops in electrical fields.

Basic formulation

P. A. Penfield and H. A. Haus. Techniques for finding force expressions for novel media.

H. A. Haus and P. A. Penfield. Force in a magnetic fluid with viscosity and hysteresis as an example of the principle of virtual power.

Generation and other applications

S. I. Cheng. Aerospace applications of electro-aerodynamic interactions.

N. J. Felici. Physical background and performance of a supersonic electro-aerodynamical high voltage generator.

M. C. Gourdine. Preliminary design of a 500 megawatt coal-fired electrogasdynamic power plant.

A. M. Marks. Optimum charged aerosols for power conversion.

J. F. Hughes and P. E. Secker. A liquid-filled high voltage electrostatic generator.

Aerosol charging and dynamics

C. D. Hendricks and J. M. Crowley. Electrohydrodynamic processes in electric field spraying of liquids.

P. Berenbrinck and G. Langbein (presented by A. Walz). Electrical phenomena connected with fast ejection of fluids.

D. S. Swatik and C. D. Hendricks. Production of intense ion beams by electrohydrodynamic spraying techniques.

W. A. Hoppel and S. Gathman. Instability produced by hyperelectrification of cloud droplets.

Post-deadline papers

R. Cade. Double layer distortion and the Dorn effect

O. Rho, C. J. Lee and L. Trefethen. Effects of radial electrostatic fields on natural convection and forced convection heat transfer to annuli.

H. A. Pohl. The dielectrophoresis of solids in liquids—normal and anomalous.

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