Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 2, 2000

ELECTROGAS- AND ELECTROHYDRODYNAMIC CONTROL OF GAS AND LIQUID JETS AND FLOWS.
1. PHYSICOMATHEMATICAL PRINCIPLES

V. S. Nagornyi

UDC 538.3:532:538.4

The physical and mathematical principles of the method of electrogas- and electrohydrodynamic conversion of electrical signals to pneumatic (hydraulic) signals and vice versa for control of gas and liquid jets and flows in electropneumohydraulic systems are considered.

1. Electrogas- and electrohydrodynamic (EHD) control of liquid or gas jets and flows is performed using the volume Coulomb or polarization forces produced at the molecular level by application of strong electric fields to the working media of converters, and attendant phenomena. This makes it possible to eliminate all mobile mechanical and electromechanical elements from the process of signal conversion in solving problems of communication, control, recording, and measurement in electrohydropneumatic systems [1–4], and, as a consequence, to increase the response and reliability of the systems. These features distinguish electropneumatic (electrohydraulic) and air-to-electric (hydroelectric) EHD converters (which are gaining in importance in all technically developed countries) from the traditional devices designed for the same purpose.

In jet electrohydraulic (electropneumatic) EHD converters, the energy of a liquid or gas jet is converted to pressure or flow rate, which are the output hydraulic (pneumatic) signals of the converters, by changing the flow regime (turbulization of the laminar jet by the ion current produced in a sharply inhomogeneous electric field), by deflecting the jet in an electric field, by EHD control of impinging jets, and by changing the jet-velocity profile [2–4]. For example, in jet electrohydraulic EHD converters, the compact liquid jet formed passes between electrodes. Control voltage, e.g., from the microcomputer output, amplified by a high-voltage amplifier, is applied to the electrodes. As a consequence, the jet is deflected relative to the receiving nozzles under the action of the resultant ponderomotive force. The pressure (or flow rate) of the working liquid changes as a function of the magnitude of jet deflection, and, being amplified by a hydraulic power amplifier, controls the corresponding hydraulic actuator. In turn, the nature of the ponderomotive forces used (polarization or Coulomb forces) determines the principle of operation, characteristics, and design of the converters.

In dispersed-jet electric devices and associated dispersed-jet electrotechnologies, a linear flow of monodisperse droplets of identical size (up to a hundred thousand droplets per second) is formed [1]. Each of the droplets can be imparted an electric charge by the induction or ionic methods according to the control program. Further, the charged droplets of the working liquid are controlled by a deflecting field. In this case, the output signal is the deflection of the droplets in the electric field. The droplets are directed to the necessary point of the surface of the corresponding object of any shape and physical nature. Thus, it is easy to implement sign synthesis, graph plotting, halftone transmission, and color imagery (by superimposition of liquid droplets of yellow, red purple, and blue colors).

St. Petersburg State Technical University, St. Petersburg 195251. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 2, pp. 25–31, March–April, 2000. Original article submitted February 25, 1998; revision submitted March 15, 1999.

So-called throttling electrohydraulic and electropneumatic EHD converters [2–4] do not contain an exposed pipeline segment, and, therefore, they can be employed on the objects subjected to large vibrations and accelerations. These converters operate by changing the hydraulic resistance to the dielectric liquid (gas) flow on a pressure pipe segment with application of a longitudinal or transverse electric field to the pipe flow. In this case, the pressure drop on a fixed length of the pipeline can be determined by both micro- and macroprocesses occurring in the fluid flow under the action of the electric field. It is shown that the microprocesses (change in the viscosity coefficient and orientation of dipole molecules by the field) have little effect on pressure losses for pipe flows of commercially pure liquids of hydraulic systems [2], although in specially designed rheological liquids, the effect of the applied electric field on the liquid viscosity can be significant.

For electrohydraulic control systems with commercially pure working dielectric liquids, EHD converters are developed that ensure a change in the velocity profile of a laminar flow by the action of a longitudinal electric field, a change in vortex generation in flow, turbulization of a laminar flow in a transverse electric field, and also a change in the characteristics of a previously swirled flow (so-called vortical EHD converters [2, 3]).

In the EHD conversion of flow parameters to electric signals, the input signal is the flow rate or pressure of the working liquids and gases, and the output signal is a component of the total current, which is subsequently amplified by a high-gain, low-noise, noise-immune electronic amplifier. In these flow rate converters, the effect of temperature and pressure on their characteristics is reduced (e.g., using differential connection of detecting electrodes) because the coefficients of mobility and diffusion of ions in the working media depend on these parameters. In label EHD flow rate converters [4], spatially limited concentrations of unipolar ions (ionic labels) are produced on most of the cross section of a turbulent flow of a gas or a dielectric liquid with a practically uniform velocity field, and the rate of motion of these labels characterizes the flow rate. The informative parameter of the volumetric flow rate in a pipeline of constant cross section is the time during which an ionic label passes through the base segment with detecting metal electrodes, in which the ionic label induces an electric current. To increase the accuracy of signal conversion, the detecting electrodes are located so that a differentiating chain is formed and the electric signal sent to the computer corresponds to the extremum of the pulse induced by the label in the detecting electrode. Thus, passage of the "electric center of gravity" of the ionic label through control cross sections of the flow is detected. In this case, irrespective of the spread of the label under the action of turbulent diffusion and the electric field, its "center of gravity" moves in the flow with the mean velocity of the flow. The base segment between the detecting electrodes is chosen with allowance for the standard deviation of the time during which the label traverses the base segment. The standard deviation characterizes the fluctuations of this time for turbulent flow. With the use of digital filtration algorithms, the label EHD flowmeter becomes a gas or liquid quantity meter. The characteristics of label EHD converters are evaluated using a mathematical model of processes occurring in a label flowmeter or quantity meter taking into account ionic interaction in the label [4].

2. For EHD control, strong electric fields with maximum strength E_0 of up to 10^7 V/m (for example, in sharply nonuniform fields) and an electrode voltage of about 10^4 V are used. A characteristic feature of EHD converters is that the strength E_0 (and, hence, the electrode voltage U) is limited by the strength $E_{\rm br}$ (voltage $U_{\rm br}$) of spark breakdown in the interelectrode gap. Spark breakdown is not an operating mode of EHD converters, and, therefore, the condition $E_0 < E_{\rm br}$ and, hence, $U < U_{\rm br}$ are always satisfied for them. In converter circuits, it is expedient to use blocking devices to eliminate spark breakdown [4].

The control signal can come from the microcomputer output. Therefore, from the viewpoint of the internal safety of the circuits and simple design of the electronic controlling devices (high-voltage amplifiers), poorly conducting, dielectric liquids and gases (mineral oils: transformer, spindle, commercial oils, etc.) are chosen as the working media of EHD converters, and the working gas is air. In this case, the currents in the interelectrode gap do not exceed several microamperes (for liquids) and tens of microamperes (for gases), and the output power of the high-voltage amplifiers is not higher than 1 W. For such low currents, the magnetic fields can be neglected, and at low flow velocities of the working media of the converters, not only liquids but also gases can be considered practically incompressible. For EHD control of jets or flows, a space electric charge is formed, as a rule, in the field in the working liquids or gases. This charge also produces an electric field, and, therefore, Poisson's equation is used in mathematical models.

In the case of unipolar conduction and isothermal processes in an incompressible fluid, the system of EHD equations can be written, neglecting bias currents, in differential form:

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\nabla)\boldsymbol{v} = \frac{F_0}{\rho} - \frac{\nabla p}{\rho} + \nu\nabla^2\boldsymbol{v} + \frac{\rho_e\boldsymbol{E}}{\rho} - \frac{0.5\varepsilon_0\nabla\varepsilon E^2}{\rho} + 0.5\varepsilon_0\nabla\Big[E^2\frac{\partial\varepsilon}{\partial\rho}\rho\Big]; \tag{2.1}$$

$$\nabla\boldsymbol{v} = 0; \tag{2.2}$$

$$\nabla\boldsymbol{E} = \rho_e/(\varepsilon_0\varepsilon); \tag{2.3}$$

$$\nabla\boldsymbol{j} + \frac{\partial\rho_e}{\partial t} = 0; \tag{2.4}$$

$$\boldsymbol{j} = \rho_e b\boldsymbol{E} + \rho_e\boldsymbol{v} - D\nabla\rho_e; \tag{2.5}$$

$$\nabla\times\boldsymbol{E} = 0. \tag{2.6}$$

Here $\boldsymbol{v}$, $\boldsymbol{E}$, and $\boldsymbol{j}$ are the flow-velocity, electric-strength, and current-density vectors, respectively, F_0 is the volume density of gravity, centrifugal forces, etc., p, ρ, ν, and ε are the pressure, density, kinematic-viscosity coefficient, and relative permittivity of the liquid (gas), respectively, ε_0 is the electric constant, ρ_e is the volume density of the electric charge, b and D are the coefficients of mobility and diffusion of ions in the liquid (gas), respectively, and t is time.

This system of equations is closed and can be used to solve any problems related to the interaction of dielectric flows and an electric field. In some cases, it is possible to neglect the volume electric forces due to the nonuniformity of the permittivity and electrostriction. In this case, Eqs. (2.1)–(2.6) are conveniently written in dimensionless form

$$\mathrm{Sr}\frac{\partial\boldsymbol{v}'}{\partial t'} + (\boldsymbol{v}'\nabla')\boldsymbol{v}' = \frac{F_0'}{\mathrm{Fr}} - \mathrm{Eu}\nabla'p' + \frac{\nabla'^2\boldsymbol{v}'}{\mathrm{Re}} + N\rho_e'\boldsymbol{E}'; \tag{2.7}$$

$$\nabla'\boldsymbol{v}' = 0; \tag{2.8}$$

$$G\nabla'\boldsymbol{E}' = \rho_e'; \tag{2.9}$$

$$\mathrm{Sr_e}\frac{\partial\rho_e'}{\partial t'} + \nabla'\boldsymbol{j}' = 0; \tag{2.10}$$

$$Z\boldsymbol{j}' = \rho_e'(\boldsymbol{E}' + \mathrm{Re_e}\boldsymbol{v}') - \frac{\nabla'\rho_e'}{\mathrm{Pe_e}}; \tag{2.11}$$

$$\nabla'\times\boldsymbol{E}' = 0. \tag{2.12}$$

System (2.7)–(2.12) includes the following dimensionless parameters: $\mathrm{Sr} = l_0/(t_0v_0)$ is the Strouhal number, $\mathrm{Eu} = p_0/(\rho v_0^2)$ is the Euler number, $\mathrm{Re} = v_0l_0/\nu$ is the Reynolds number, $\mathrm{Fr} = v_0/(gl_0)$ is the Froude number, g is the acceleration of gravity, $N = \rho_{e0}E_0l_0/(\rho v_0^2)$ is an EHD-interaction parameter which is the ratio of the volume density of electric energy to the volume density of hydro- or gas-dynamic energy, $G = \varepsilon_0\varepsilon E_0/(l_0\rho_{e0})$ is a number that describes the relation between the applied external electric field and the internal field of the charge, $Z = j_0/(b\rho_{e0}E_0)$ is the relative density of conduction current, $\mathrm{Re_e} = v_0/(bE_0)$ is the electric Reynolds number, which describes the relation between convective current and conduction current, $\mathrm{Pe_e} = bE_0l_0/D$ is the electric Peclet number, which describes the relation between the rate of motion of the charges in the electric field and the rate of their diffusion drift, $\mathrm{Sr_e} = \rho_{e0}l_0/(j_0t_0)$ is the electric Strouhal number, which describes the relation between the current density in the steady and transition regimes, v_0, p_0, E_0, j_0, ρ_{e0}, t_0, and l_0 are the scalar characteristic scales, and $\boldsymbol{v} = v_0\boldsymbol{v}'$, $p = p_0p'$, $\boldsymbol{E} = E_0\boldsymbol{E}'$, $\boldsymbol{j} = j_0\boldsymbol{j}'$, $\rho_e = \rho_{e0}\rho_e'$, $t = t_0t'$, and $l = l_0l'$. The dimensionless operators take the form $\nabla' = \nabla/l_0$ and $\nabla'^2 = \nabla^2/l_0^2$.

In the analysis of particular types of converters, the ratio of the controlling external electric field to the internal field of the charge is taken into account by an appropriate choice of the number G in the dimensionless Poisson's equation (2.9). For gas jets and flows in which the volume charge density produced in EHD control ρ_e is several orders of magnitude lower than those in the working dielectric liquids (ε is also 2 or 3 times smaller), the effect of the internal field of charges on the converter performance can be ignored in some cases as a first approximation. However, with more stringent requirements for the accuracy of conversion of signals (for example, in label EHD gas flow rate converters) into an electrical signal, ionic interaction in the label is taken into account in the equation of transfer of the ionic label [4].

Use of low-viscosity, nonconducting, weakly polar liquids (for example, mineral oils) as working media has a considerable practical advantage in EHD control. Therefore, in flow control, the main electrophysical properties of working media are as follows [2–4]: relative permittivity $\varepsilon = 1$–3 (dispersed-jet electric devices often use water-based liquids with ε much higher than that mentioned above), specific conductivity $\sigma = 10^{-14}$–10^{-11} $(\Omega \cdot \mathrm{m})^{-1}$, coefficient of mobility of ions in working liquids $b \sim 10^{-8}$ m^2/(V $\cdot$ sec), coefficient of mobility of ions in working gases $b \sim 10^{-4}$ m^2/(V$\cdot$sec), diffusivity of ions in working liquids $D \sim 10^{-10}$ m^2/sec, and diffusivity of ions in working gases $D \sim 10^{-5}$ m^2/sec.

From practice it is known that the lower the viscosity of the working liquids, the more effective the EHD control. Therefore, the kinematic-viscosity coefficient in the liquids ν at 20°C does not exceed $(30$–$40) \cdot 10^{-6}$ m^2/sec, and at 50°C, it is $(1.7$–$14.0) \cdot 10^{-6}$ m^2/sec for a liquid density $\rho = 900$–800 kg/m^3. The working gas in EHD converters is air whose density under standard atmospheric conditions (temperature 20°C and pressure 0.101325 MPa) is equal to 1.205 kg/m^3, and the kinematic-viscosity coefficient at 0°C is $13.2 \cdot 10^{-6}$ m^2/sec, and it increases with increase in temperature.

3. We evaluate qualitatively the order of magnitude of the electrical parameters needed for implementation of EHD control. For this, we assume that a dielectric medium flowing with velocity v_0 is acted upon by an electric field with the maximum permissible strength E_0 at which spark breakdown of the interelectrode gap does not occur (as noted above, spark breakdown is a nonoperating mode of converters).

In EHD control, an electric field most often affects a charged flow of a liquid or a gas. Therefore, we evaluate the necessary magnitude of electric charge that should be introduced into the flow for effective EHD control, assuming that the densities of the electric and hydro- or gas-dynamic energy should be commensurable:

$$\rho_{e0}E_0l_0 = \rho v_0^2/2.$$

Here l_0 is a characteristic linear dimension (for example, the interelectrode gap). Then,

$$\rho_{e0} = \rho v_0^2/(2E_0l_0). \tag{3.1}$$

The value of l_0 is selected from the requirement of minimum dimensions of EHD devices and limitations on the converter electrode voltage (about 10^4 V).

We set $l_0 = 10^{-3}$ m, $E_0 = 10^7$ V/m, $v_0 = 1$ m/sec, and working liquid density $\rho \sim 10^3$ kg/m^3. Then, from (3.1) it follows that the necessary volume density of electric charges in the liquid is $\rho_{e0} = 5 \cdot 10^{-2}$ C/m^3.

For gases ($\rho \sim 1$ kg/m^3) at $E_0 = 10^6$ V/m, from (3.1) we have $\rho_{e0} = 5 \cdot 10^{-4}$ C/m^3. In this case, the quantity of ions in 1 m^3 of a gas is equal to $\rho_e/e = 3 \cdot 10^{15}$. Here $e = 1.6 \cdot 10^{-19}$ C is the electron charge. Since 1 m^3 of a gas contains approximately 10^{25} molecules under standard conditions, the ratio of charged molecules to neutral molecules (degree of ionization) is about 10^{-8} %. Hence, for EHD control, it suffices to use flows with a low degree of ionization.

It should be noted that without spark breakdown of the interelectrode gap, the above-mentioned maximum field strengths (about 10^7 V/m) cannot be attained using homogeneous fields in gases, in particular, in air, for which the breakdown field strength is $3 \cdot 10^6$ V/m. Such maximum field strengths are close to the static breakdown strengths for dielectric working liquids (mineral oils). However, as shown below, they are easily attainable in rather narrow areas in sharply inhomogeneous fields using simple electrode designs.

Such values of the degree of ionization can be achieved using x-rays, ultraviolet radiation, radioactive materials, nonequilibrium ionization detected in flames, electrokinetic phenomena, or the peripheral area of a corona discharge in gases and its analog in liquids. It is desirable that the selected source of ionization ensure (if necessary) a uniform distribution of ions in the jet or flow, fairly long lifetime of the ions, precise control of the available ionization, and the operational safety of the maintenance personnel. This is achieved by means of a corona discharge in gases [2, 5, 6] or processes occurring in dielectric liquids in strong, sharply inhomogeneous electric fields [2]. An interesting property of a corona discharge is that formation of electrons and ions by impact ionization of gas occurs only in a narrow corona-discharging layer in the immediate proximity of the large-curvature electrode. In the so-called peripheral area of the corona discharge, which is located behind the corona-discharging layer, there is a unipolar flow of ions having the same sign as the corona-discharging electrode potential and directed to the other electrode.

Let us show that by means of a corona discharge, it is possible to produce volume charge densities necessary for EHD control. We assume that a device for imparting a charge to flows of the working medium has the form of concentric metal spheres of radii r_0 and r_1 ($r_0 \ll r_1$) to which voltage is applied. Taking into account spherical symmetry, from relations (2.3)–(2.5), it is easy to obtain a system of equations for the corona. In this case, Poisson's equation (2.3) is written as

$$2\frac{E_r}{r} + \frac{dE_r}{dr} = \frac{\rho_e}{\varepsilon_0\varepsilon}, \tag{3.2}$$

where $\varepsilon_0\varepsilon$ is the absolute permittivity of the working medium, E_r is the electric-field strength in the space between the spheres, and r is the current radius.

We estimate qualitatively the order of magnitude of the maximum attainable charge density on the external boundary of the corona-discharging layer. For this, as a first approximation within the internal region of the corona, we set $E_r = E_{\max} = \text{const}$. Then, from Eq. (3.2), we obtain

$$\rho_{e\max} = 2\varepsilon_0\varepsilon E_{\max}/r. \tag{3.3}$$

The maximum electric-field strength is at the electrode with minimum curvature radius, i.e., at the corona-discharging electrode in the internal region of the corona, where bipolar conduction takes place. However, we are interested in the flow of unipolar ions in the peripheral area of the corona. Therefore, in (3.3) $E_{\max}$ is the strength on the boundary of the internal zone of the corona. Setting $r = r_c$, where r_c is the outside radius of the corona-discharging layer, in which impact ionization takes place, for the maximum density of the unipolar charge, we obtain the expression

$$\rho_{e\max} = 2\varepsilon_0\varepsilon E_{\max}/r_c. \tag{3.4}$$

For air, $\varepsilon_0\varepsilon \sim 10^{-11}$ F/m and $E_{\max} \sim 10^6$ V/m. For $r_c = 10^{-4}$–10^{-3} m, which is typical of EHD converters, from (3.4) we have $\rho_{e\max} \sim 10^{-1}$–$10^{-2}$ C/m^3, at which EHD control of gas flows is possible.

The quantity $E_{\max}$ is one or two order of magnitude higher in dielectric liquids than in air. The low mobility of charges in liquids makes it difficult to create in them conditions for of impact ionization. Therefore, the physical mechanisms of formation of unipolar charges in sharply inhomogeneous electric fields are different for liquids and gases. Practice shows that one can attain higher values of $\rho_{e\max}$ in the working liquids of EHD converters than in gases.

In some cases, it is possible to ignore the thickness of the corona-discharging layer and, as a first approximation, to set $r_c \approx r_0$ in expression (3.4). Then,

$$\rho_{e\max} \approx 2\varepsilon_0\varepsilon E_{\max}/r_0. \tag{3.5}$$

Thus, to increase the effectiveness of EHD converters using a corona discharge with allowance for (3.5), it is necessary to select the smallest possible radius of rounding of the corona discharging electrode. The fluid charge densities obtained by this method correspond to the ρ_{e0} found from condition (2.1) of commensurability of the gas-dynamic (hydrodynamic) and electric forces, and they are sufficient for control of EHD converters.

The processes of imparting unipolar charge ρ_e to a gas or a liquid and production of the controlling volume force $F = \rho_e E$ can be made coincident in time by using strong, sharply inhomogeneous electric fields. To calculate the static characteristics of EHD converters from (2.1)–(2.6) or (2.7)–(2.12), it is necessary to find the distributions of the volume charge density ρ_e and the electric-field strength E in the interelectrode gap taking into account the design features of EHD converters, the boundary conditions, and the adopted assumptions. The maximum strength $E_{\max}$ is attained in the immediate proximity of the electrode with a small radius of rounding (corona-discharging electrode in the gas). This simplifies the design and electric circuit of EHD converters and is certainly an advantage of the signal conversion method considered. For air and dielectric working liquid, the maximum values of the controlling volume force are 10^5 and 10^7 N/m, respectively.

Thus, the value of the control volume force is limited, and this limits the value of the output gas- or hydrodynamic power of EHD converters.

REFERENCES

1. V. S. Nagornyi, *Dispersed-Jet Electric Recording Devices* [in Russian], Mashinostroenie, Leningrad (1988).
2. A. A. Denisov and V. S. Nagornyi, *Eletrohydro- and Electrogas-Dynamic Automatic Devices* [in Russian], Mashinostroenie, Leningrad (1979).
3. V. S. Nagornyi and A. A. Denisov, *Automatic Devices of Hydro- and Pneumatic Systems* [in Russian], Vysshaya Shkola, Moscow (1991).
4. A. A. Denisov, V. S. Nagornyi, M. M. Telemtaev, V. P. Voevodin, *Automatic Control System for Dosing Processes* [in Russian], Mashinostroenie, Leningrad (1985).
5. N. A. Kaptsov, *Electrical Phenomena in Gases and Vacuum* [in Russian], Gostekhteorizdat, Moscow (1950).
6. Yu. P. Raizer, *Gas Discharge Physics* [in Russian], Nauka, Moscow (1992).