CHARACTERISTICS OF THE STAGES OF AN ION-CONVECTION PUMP

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Results are presented from theoretical and experimental studies of a pump for handling insulating liquids. Various types of ionizer are compared.

When a unipolar discharge passes through a neutral medium, the charge carriers interact with the neutral particles, which can be used to produce a pressure difference. This effect is clearly seen in the outer part of a corona discharge and is known as the corona wind.

Stuetzer [1, 2] made the first studies on the use of a corona discharge for pumping insulating liquids, but his theoretical studies involved certain assumptions, and the agreement with experiment was not good.

Here we give a theoretical analysis of such a pump. The calculations are compared with experiments on stages of various designs.

Symbols: p pressure, V speed of neutral liquid, ρ density, ξ frictional loss coefficient, x distance along axis of channel, E field strength, ρ_i charge density, V_i velocity of charge carriers, U potential, j current density, N power, ε dielectric constant, b mobility, μ dynamic viscosity.

Any design for such a pump (Fig. 1) has two zones in the region of motion of charges between the electrodes: the corona layer (a quasineutral region of passage of electron avalanches) and an outer region (the region of unipolar charge transport) [3]. The operation is described by calculating the outer region of the discharge, as this directly produces the pressure difference. The physical processes in the outer region are described via the following system of equations, which have been written for the practical case of small relative charge concentration without allowance for the diffusion current or the inherent conduction of the liquid:

$$(\rho V\nabla)\,\mathrm{V} + \nabla p - \rho_i \mathrm{E} - \mu\nabla^2 \mathrm{V} = 0, \quad \operatorname{div} \mathrm{V} = 0 \tag{1}$$

$$\operatorname{div}(\mathrm{V}_i \rho_i) = 0, \quad \mathrm{V}_i = \mathrm{V} + b\mathrm{E}, \quad \operatorname{div} \mathrm{E} = \rho_i / \varepsilon, \quad \operatorname{rot} \mathrm{E} = 0 \tag{2}$$

This system is a combination of the hydrodynamic equations for the ions and neutral particles with Maxwell's equations for the electric field: (1) gives the equations of motion and continuity for the neutral component, while (2) gives the same for the ions, together with the first pair of Maxwell's equations, which have been written with the external and internal magnetic fields neglected.

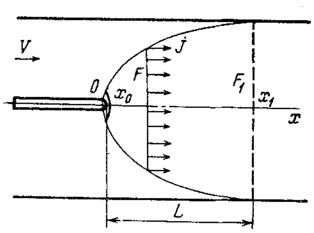

Fig. 1

We give the solution for the quasi-one-dimensional case, which is taken as a mathematical model for describing the phenomenon.

In this model (Fig. 1), the actual two-component flow is related to two interacting canonical flows whose parameters are constant over the cross-section: a flow of neutral liquid in a channel of constant cross-section F_1 and a flow of charge from the point, whose current

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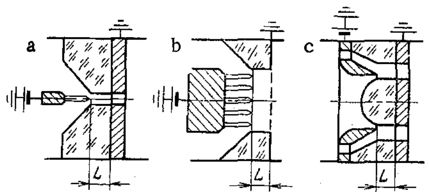

tube is a paraboloid of rotation whose variable cross section F is related to F_1 by $F = F_1(x/x_1)$.

System (1) and (2) then becomes

$$\frac{dp}{dx} - \frac{x}{x_1}\rho_i E + \frac{\xi}{x_1}\frac{\rho V^2}{2} = 0, \qquad \frac{dV}{dx} = 0 \tag{3}$$

$$\frac{d(V_i \rho_i x)}{dx} = 0, \quad V_i = V + bE, \quad \frac{d(Ex)}{x\,dx} = \frac{\rho_i}{\varepsilon} \tag{4}$$

Here the third term in the first equation characterizes the frictional loss and has been introduced by analogy with the loss term in Bernoulli's equation.

We combine Eqs. (4) to get

$$\varepsilon (V + bE)\frac{d(Ex)}{dx} = j_1 x_1$$

in which j_1 is the current density in the cross section F_1. This equation can be transformed to one in which the variables are separated:

$$\frac{dx}{x} = \frac{V\varepsilon + b\varepsilon E}{j_1 x_1 - V\varepsilon E - b\varepsilon E^2}\,dE$$

This equation must be integrated for the external region in order to find the distribution of E. The integration gives a lengthy expression that can, with little error, be reduced to the following:

$$E = \left[\frac{V^2}{4b^2} + \frac{j_2 x_1}{\varepsilon b}\left(1 - \frac{x_0^2}{x^2}\right) + E_0\frac{x_0^2}{x^2}\left(\frac{V}{b} + E_0\right)\right]^{1/2} - \frac{V}{2b}$$

This gives the distribution as a straight line almost parallel to the x axis and independent of E_0. Deviation from linearity occurs only in the short initial region where $x_0/x \approx 1$.

We need only the integral characteristics over the entire distance between the electrodes in order to find the pressure and potential differences, i.e., the area under the E(x) curve, so that the integration may be performed with the field distribution written as

$$E \approx \left(\frac{V^2}{4b^2} + \frac{j_1 x_1}{\varepsilon b}\right)^{1/2} - \frac{V}{2b}$$

This is integrated with $U_1=0$ for the anode to get the voltage-current relation for a corona discharge in a moving liquid:

$$U_0 = L\left(\frac{V^2}{4b^2} + \frac{j_1 L}{\varepsilon b}\right)^{1/2} - \frac{V}{2b}L \tag{5}$$

in which L is the distance between the electrodes.

The analogous expression for the one-dimensional approximation is

$$U_0 = \frac{\varepsilon b}{3j}\left\{\left[\frac{2j}{\varepsilon b}L + \left(\frac{V}{b} + E_0\right)^2\right]^{3/2} - \left(\frac{V}{b} + E_0\right)^3\right\} - \frac{V}{b}L \tag{6}$$

Here E_0 is the field at the point when the corona discharge starts, i.e., in the absence of space charge.

Consider now the pressure set up by the passage of a current.

For this purpose we integrate the equation of motion [3], putting in it the value of ρ_i.

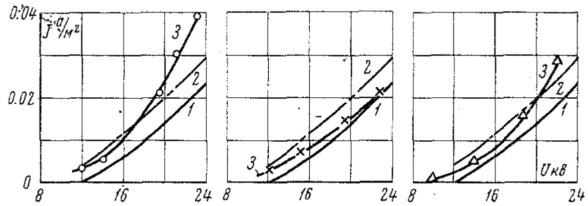

Fig. 3

We put the inlet pressure as $p_0=0$, which can always be done for an incompressible liquid, and get

$$p_1 = \frac{j_1}{b}L + \frac{\varepsilon V^2}{4b^2} - \frac{\varepsilon V}{b}\left(\frac{V^2}{4b^2} + \frac{j_1 L}{\varepsilon b}\right)^{1/2} - \xi\frac{\rho V^2}{2} \tag{7}$$

The analogous formula for the one-dimensional approximation is

$$p_1 = \frac{j}{b}L + \frac{\varepsilon V}{b}\left(\frac{V}{b} + E_0\right) - \frac{\varepsilon V}{b}\left[\frac{2j}{\varepsilon b}L + \left(\frac{V}{b} + E_0\right)^2\right]^{1/2} - \xi\frac{\rho V^2}{2} \tag{8}$$

The following is the useful hydrodynamic power produced by the pump per m^2 of channel in this model:

$$N_1 = P_1 V = \frac{j_1 V}{b}L + \frac{\varepsilon V^3}{4b^2} - \frac{\varepsilon V^2}{b}\left(\frac{V^2}{4b^2} + \frac{j_1 L}{\varepsilon b}\right)^{1/2} - \xi\frac{\rho V^3}{2} \tag{9}$$

and in the one-dimensional approximation:

$$N_1 = \frac{jV}{b}L + \frac{\varepsilon V^2}{b}\left(\frac{V}{b} + E_0\right) - \frac{\varepsilon V^2}{b}\left[\frac{2j}{\varepsilon b}L + \left(\frac{V}{b} + E_0\right)^2\right]^{1/2} - \xi\frac{\rho V^3}{2} \tag{10}$$

The electrical power consumed by 1 m^2 of channel is here

$$N_2 = j_1 U_0 = j_1 L\left(\frac{V^2}{4b^2} + \frac{j_1 L}{\varepsilon b}\right)^{1/2} - \frac{V}{2b}L \tag{11}$$

The analogous expression for the one-dimensional case is

$$N_2 = \frac{\varepsilon b}{3}\left\{\left[\frac{2j}{\varepsilon b}L + \left(\frac{V}{b} + E_0\right)^2\right]^{3/2} - \left(\frac{V}{b} + E_0\right)^3\right\} - \frac{jV}{b}L \tag{12}$$

The efficiency η is the ratio of the two powers, and it can be shown that $\eta \to \eta_{max}$ when $b \to 0$. In this model,

$$\eta = 1 - (\xi\rho / \varepsilon)\,(LV / 2U_0)^2 \tag{13}$$

This shows that η increases as $\xi\rho/\varepsilon$ decreases. The loss arises from the viscosity, so we may say that the pump is more efficient in pumping liquids of low density and viscosity that have high dielectric constants.

If $\xi=0$, $\eta \to 1$ as $b \to 0$, i.e., the pump is most efficient with liquids of small b, such as petroleum distillates and freons, whose b are of the order of 10^{-7} m^2/V-sec. Then (13) can be used to estimate η.

We have neglected conduction in the liquid, since this must be negligible if the pump is to be efficient, e.g., 10^{-11} to 10^{-14} $ohm^{-1} cm^{-1}$ for oil products and organic heat carriers. Otherwise, energy will be consumed by conduction without making a contribution to the pressure difference. For this reason, the pump cannot be applied to water, electrolytes, etc.

Let us now compare theory with experiment. Experiments were carried out for three types of step (Fig. 2), where a) is of the single-needle type, b) is of the many-needled type, and c) is cylindrical.

We tested the designs shown in Fig. 2, measuring the liquid flow, pressure difference, corona current, and electrode voltage on technical kerosene with a negative corona.

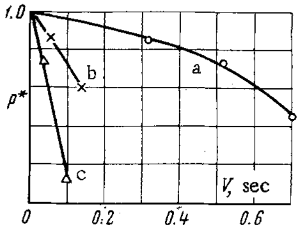

Fig. 4

We recorded voltage-current curves for the three designs at zero flow with a distance L=3.5 mm between the electrodes (Fig. 3); here 1 represents the one-dimensional result, 2 the above model, and 3 the experimental result. For each curve we show the theoretical results for the one-dimensional case and the above model, both of which agree well with experiment.

Figure 4 gives typical p*(V) curves for the above designs, in which p* is the ratio of the actual pressure difference to that at zero flow. It is clear that the performance is worst for the design with the cylindrical ionizer, with the multiple-point design somewhat better, and the single-point design the best. The first two designs have measured efficiencies not exceeding 10%. There are two general reasons for this poor performance: 1) these designs did not allow large current densities to be attained. The electric fields of adjacent points or adjacent parts of the cylindrical electrode interact, with the result that the corona current for a given potential is less than for a single point or (if the points are far enough apart) increases much less rapidly than the area of the channel. 2) The design of the stage is decisive for the interaction of the charge carriers with the neutral liquid. Efficient working requires the electric field vector to coincide in direction with the neutral-particle velocity over as much of the volume as possible. Theory and experiment show that the single-point design approximates best to this, while the cylinder design is the worst. The multipoint design has the charged particles moving to the anode grid in narrow beams that do not interact with the body of the liquid.

The one-point design is the best, and the other designs should be used only when it is necessary to obtain large flow rates from small devices and efficiency is merely a secondary consideration.

Figure 5 shows the pressure characteristics of a single-point design and also the dependence of η on the velocity at constant voltage. The theoretical curves from (5)-(12) are also shown. It is clear that the model used here gives better general agreement with experiment than does the one-dimensional approximation. The discrepancy between theory and experiment within the working range of speeds does not exceed 10% for the pressure and 25% for the efficiency.

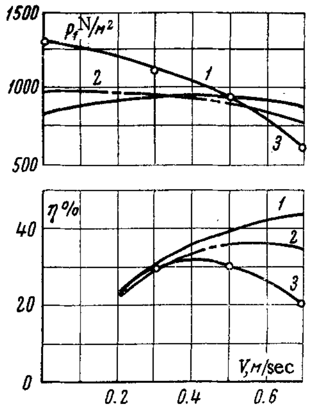

Fig. 5

These studies show that the single-point design is the best and that its performance can be predicted accurately from the model used here. This design of stage should be used in a multistage pump.

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