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Research on wind energy conversion by electrofluid dynamic processes(*)

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THE PRINCIPLE of an EFD generator is similar to that of a van de Graaff machine, but the electric charges are carried along by a gas flow instead of being transported by an insulating strap. The possible application to an EFD wind generator is treated here. We succeeded in obtaining a positive energy balance with a small scale model placed in a wind tunnel by producing charged droplets by an electrohydrodynamic process. The efficiency is too poor for practical application; nevertheless it is better than the one which could be predicted if the droplet charges followed Vonnegut's law for EHD spraying.

Zasada generatora EFD przypomina zasadę maszyny van de Graffa z tym, że ładunki elektryczne przenoszone są tu przez strumień gazu a nie przez paski izolacyjne. Omawiana jest tu możliwość konstrukcji takiego generatora, który produkowałby elektryczność, wykorzystując energię wiatru. Autorowi udało się uzyskać dodatni bilans energetyczny takiego procesu za pomocą małego modelu generatora umieszczonego w tunelu aerodynamicznym. Wydajność procesu jest zbyt niska do celów praktycznych, choć jest wyższa niż wynikałoby to z zastosowania prawa Vonneguta do ruchu kropel naładowanych.

Принцип действия электрогидродинамического генератора напоминает принцип действия генератора Ван-де-Граафа, с тем, что электрические заряды переносятся здесь потоком газа, а не изоляционными лентами. В этой статье изучается возможюсть приспособление того же принципа к Э.Г.Д. ветрогенератора. Автору удалось получить положительный энергетический баланс такого процесса при помощи малой модели генератора, помещенного в аэродинамическом туннеле. Эффективность процесса однако слишком низка для практических целей, хотя она более высокая, чем следовало бы это из применениязакона Воннегута для движения заряженных капель.

1. Introduction

ELECTROFLUID dynamic (EFD) generators are devices allowing the direct conversion of the kinetic energy of a flow into electrical energy. Their principle is similar to that of a Van de Graaff generator but the charges are carried to the collector by gas flow instead of being transported by an insulating belt. These devices typically furnish high voltages and low current densities.

To be carried by the flow in spite of the electric field which opposes their arrival on the collector, the charge carriers must have a low electrical mobility. This mobility, k, is defined by

$$k = u/E, \tag{1}$$

where u is the average drift speed acquired by a charged particle placed in an electric field E.

Very high voltage EFD generators were designed as early as the 1930's. Figure 1 shows the device developed by PAUTHENIER [1]. Dust seeded air (1 to 10 μm particles) is put

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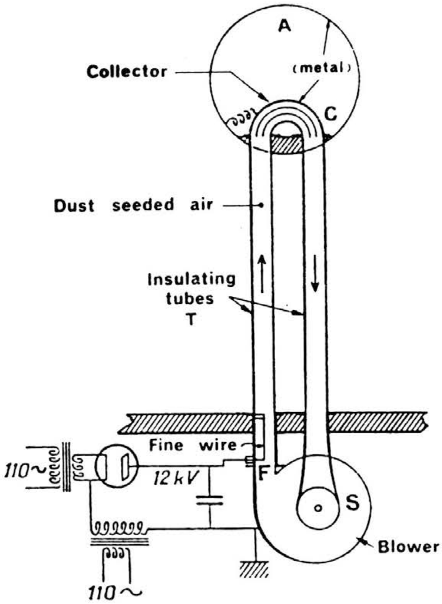

FIG. 1. Pauthenier's very high voltage generator.

into motion by the blower *S* and flows at the speed of 50 m/s in the insulating tubes *T*. The particles are charged at *F* by the corona charging method and lose their charge on the metallic walls *C* against which they are projected by centrifugal force. The voltage on the sphere *A* reached 1.2 million volts. There was considerable renewed interest in EFD generators as of 1960 and many investigations were conducted on high-pressure and high-speed flows in which very high power densities are obtained [2].

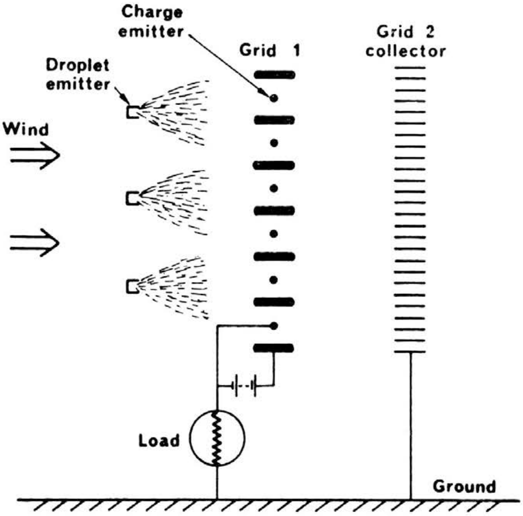

FIG. 2. Example of an EFD wind power system configuration.

The same energy conversion principle could be applied to wind. Schematically, the device would then include at least two parallel "grids": an upstream grid made up of an array of charged particle emitters and a downstream grid acting as a collector. This system would have the advantage of not being subjected to the surface limitations of conventional wind power systems and could be less costly.

In a patent filed in Hungary in 1931, and later in Germany, KERTÉSZ [3] had already considered the possibility of avoiding the problems of charged particle collection by taking energy between the emitters of the first grid (G1) and the ground, as indicated in Fig. 2. In this way, all the current emitted goes through the load. The second grid (G2) is connected to the ground and the part of the charges which escape this collector finally return to earth downstream of the system.

That device considered the charges as simply produced by corona discharge in the ambient air, by applying a voltage of a few thousand volts between an array of fine wires and an array of intermediate plates. It is fully established today that the mobility of ions produced by this method (about 1.8×10^{-4} m/s/V/m for the positive ions of the air) is too high to enable the system to deliver a significant amount of energy. Going through the ionizer, the dust in suspension in the air picks up ions and then forms charge carriers of low mobility. However, even in the most highly polluted zones of the earth, the concentration of dust is much too small to contribute significantly to the increase in conversion efficiency. It is thus necessary to have aerosol generators upstream of the system (see Fig. 2) or to directly produce a charged aerosol at the first grid (see Fig. 6). In both cases the aerosol should be made up essentially of water droplets to avoid pollution.

The most difficult problem to solve in designing an EFD wind power system is the production of aerosols having suitable properties, while using an energy clearly lower than the recoverable energy. These properties and the possible means of producing aerosols are examined below.

2. Theoretical results

The kinetic power of the wind through a section of surface S is equal to $1/2\ \varrho S U_0^3$ where ϱ is the density of the air and U_0 the wind velocity. In the conversion section of a generator, the flow velocity is reduced and takes the value U. According to Betz' theory, the maximum power of a generator is obtained when $U/U_0 = 2/3$. The power per unit area of an ideal generator is then

$$P_{\max} = \frac{16}{27}\left(\frac{1}{2}\varrho U_0^3\right). \tag{2}$$

In the particular case of EFD generators, two phenomena limit the performance levels:

a) The electric field, which is at its maximum on the downstream side of the first grid, cannot exceed the breakdown field in air, E_c.

b) The field creates a charge carrier slip velocity in relation to the air, reducing the effectiveness of charge transport by the flow.

A one-dimensional theory taking into account these effects was developed by LAWSON, VON OHAIN and WATTENDORF [4] for two-grid generators considered to be semi-infinite planes. The power density of a generator when its performance is not limited by the breakdown field is

$$P = \frac{1}{2}\varrho U_0^3 4\left(\frac{U}{U_0}\right)^2\left(1-\frac{U}{U_0}\right)\left[1-\frac{4}{3}k\left(\frac{\varrho}{\varepsilon}\right)^{\frac{1}{2}}\left(\frac{U_0}{U}-1\right)^{\frac{1}{2}}\right], \tag{3}$$

where ε is the dielectric constant for air. The value of the ratio U/U_0 for which P is at its maximum value depends on the mobility k.

For certain critical values U_{0c} of the wind velocity, the field E_1 on the first grid becomes equal to the breakdown field E_c. When U_0 is greater than U_{0c}, E_1 must remain equal to E_c and the optimum ratio of U/U_0 is given by the equation

$$\left(\frac{U}{U_0}\right)^2-\left(\frac{U}{U_0}\right)+\frac{1}{4}\frac{\varepsilon E_c^2}{\varrho U_0^2}=0 \qquad \left(\text{avec}\ \frac{U}{U_0}>\frac{1}{2}\right). \tag{4}$$

The maximum power density is then calculated using the optimum values of U/U_0 in Eq. (1).

Figure 3 gives the results obtained with:

$$\varrho = 1.225\ \mathrm{kg/m^3}; \quad E = 3\times10^6\ \mathrm{V/m}; \quad \varepsilon = 8.86\times10^{-12}\ \mathrm{A-s/V-m}.$$

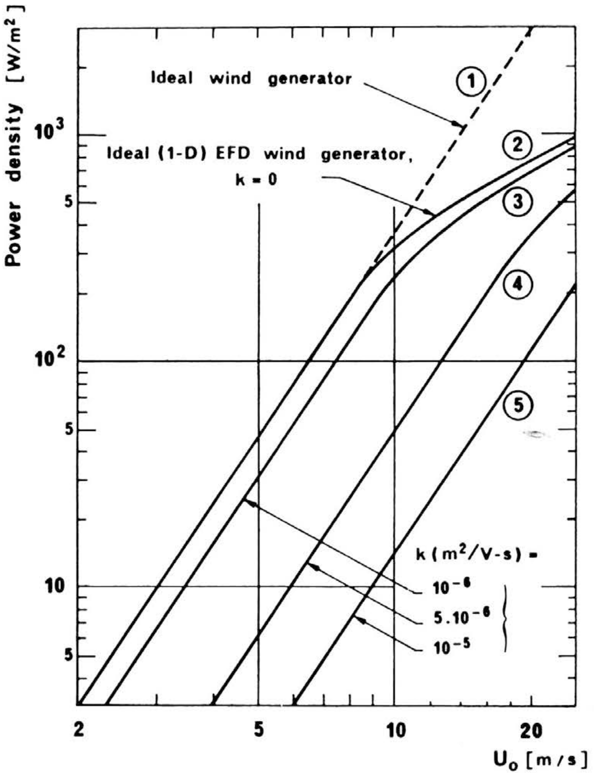

FIG. 3. Power densities as a function of wind velocity for an ideal generator (1) and for an ideal (2) or semi-ideal (3 to 5) EFD generator based upon the one-dimensional theory.

It should be noted that the one-dimensional theory assumes that the grids are fully pervious to the flow and impervious to the electric field. More thorough calculations were carried out by MINARDI *et al.* [5] to take into account the drag of the grids and the effects of a two-dimensional configuration of the electric field on the input grid. The preceding results, however, make it possible, among other things, to determine within which range should fall the electrical mobilities of the charge carriers in order to obtain a generator of suitable efficiency. Since the charged particle production rate should increase as the particle charge decreases, it appears that mobilities of the order of 10^{-6} m^2/V$-$s correspond to an acceptable compromise. For this value of k, the one-dimensional theory indicates a maximum power density of about 200 watts/m^2 for a wind velocity of 10 m/s. A power density half that value would still constitute a very valid achievement.

3. Production of charged aerosols

To test the possibilities of EFD generators, MINARDI *et al.* [5, 6] conducted several wind tunnel tests on models of about 0.2 m^2. The configuration was similar to the one in Fig. 2, i.e. the aerosol was produced upstream of the first grid and charged by the corona effect. When the aerosol is produced by the spraying of liquid nitrogen in moisture saturated air, the electric power density reached 78 W/m^2 for a flow velocity U of about 11.5 m/s in the system. It is thus demonstrated that high electric powers can be obtained provided charged aerosols with suitable properties are available. However, the method used in these experiments for producing the aerosol obviously leads to energy cost several orders of magnitude higher than the available energy.

Many processes were considered for producing fine droplets with a low energy cost [6, 7, 8], including conventional pneumatic methods, electrohydrodynamic spraying or even the breakup of charged water microbubbles. To our knowledge, no experiment has demonstrated that a positive energy balance could be obtained by one of these processes.

The difficulty of the problem can be illustrated by calculating the production rate and the droplet size required to operate a generator of 1 m^2 located 20 meters above the ground and delivering an electric power of 100 watts under a voltage of 400 kilovolts. Let us assume that the mobility of the droplets is $k = 10^{-6}$ m^2/V$-$s, and that the power P_p used for pumping water up to the required height is a more or less large fraction of the electric power obtained. The number N of droplets to be furnished per second, and the radius r of these droplets, are then imposed. They are given in Table 1.

Table 1.

P_p (watt)	N (number/s)	r (micron)
10	18.7×10^{10}	4
1	64.1×10^{10}	1.23
0.1	80.4×10^{11}	0.36

Thus, even if 10% of the electric power obtained is used up for water pumping, it is necessary to produce, each second, for each square centimeter of generator, over 18 million droplets of 8 — micron diameter.

Such high production rates for such fine droplets do not appear to be achievable by usual methods with an acceptable energy cost. It is thus necessary to consider other methods and, in particular, an electrohydrodynamic spraying method, some details of which are given in the following paragraph.

4. EDH spraying

When a potential difference of a few kilovolts is applied between a plate and a metallic capillary supplied with liquid under a pressure near zero (Fig. 4a), the meniscus can take the form of a cone extended at its apex by a very fine jet whose breakup gives rise to charged droplets (Fig. 4b). This phenomenon has formed the subject of a number of investigations [9–12]. Assuming that the energy of the drops is minimal, VONNEGUT and NEUBAUER [10] established the following relationship between the size and the charge to volume ratio, q/v, of the droplets:

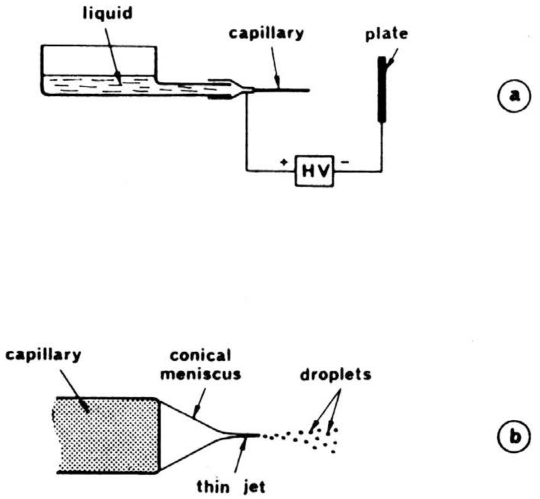

FIG. 4. a) EHD spraying device. b) Spraying phenomenon at end of capillary.

(5) $$r^3 = \frac{10^{-9}A}{4\pi(q/v)^2},$$

where A is the surface tension of the liquid.

This equation is not always confirmed, but it makes it possible to determine approximately the size of the particles emitted from two easily measurable parameters: q/v is in fact equal to the ratio i/v of the current delivered by the high-voltage source to the volume flow rate of the liquid in the capillary.

Combining Eq. (5) with Cunningham's drag formula, it is possible to calculate the mobility of the droplets according to their radius. Figure 5 gives the results obtained. It shows that mobility is always higher than 10^{-5} $m^2/V-s$, i.e. too high for the charge carriers in an EFD generator.

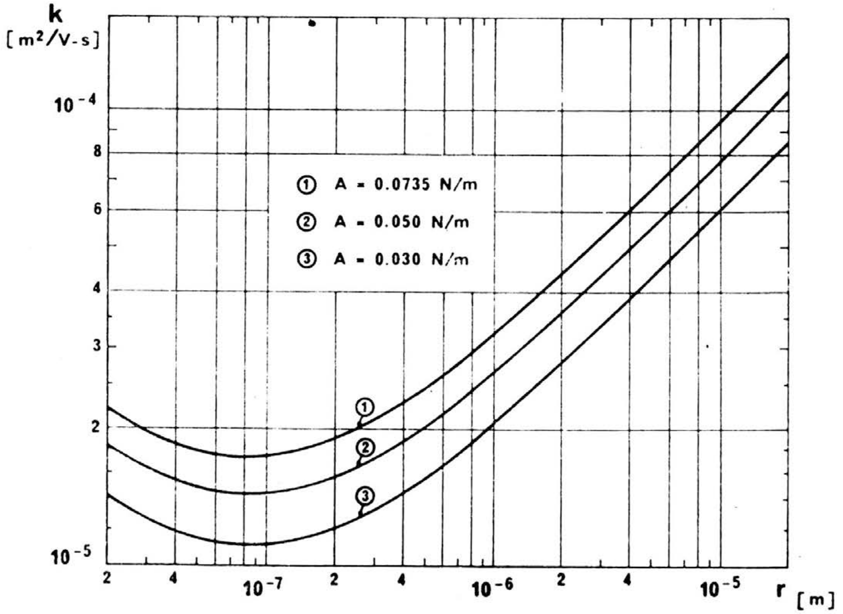

FIG. 5. Mobility of droplets produced by EHD spraying when charge corresponds to Vonnegut's law.

This spraying method, however, yields fine droplets with a high production rate. For example, with pure water and with a single emitting cone, we obtained a production of about 20 million droplets per second with an average radius equal to 0.6 micron. For this reason we carried out a series of tests on a small converter model without attempting to modify the mobility of the particles during this first research phase.

5. EFD conversion tests using EHD spraying

A part of the emitting grid of the test set-up is shown schematically in Fig. 6a. Two pairs of uprights in insulating material, spaced 35 cm, support two series of horizontal metallic bars. The first series is made up of streamlined plates spaced vertically by 2 cm. The second series is made up of tubes supplied with a liquid. In the middle part of five of these tubes (only two are shown) are placed 20 capillaries spaced 5 mm from each other. Thus the useful surface area of the grid is only 0.012 m^2. It comprises 100 emitters.

The tubes were supplied with demineralized water containing 0.2% surfactant. The dynamic surface tension of this mixture is at least 0.05 N/m. The voltage V_p applied between the plates and tubes (Fig. 6b) was -4000 volts, and the load R was 211.10^8 ohms. For a flow velocity U equal to 9 m/s, the following results were obtained.

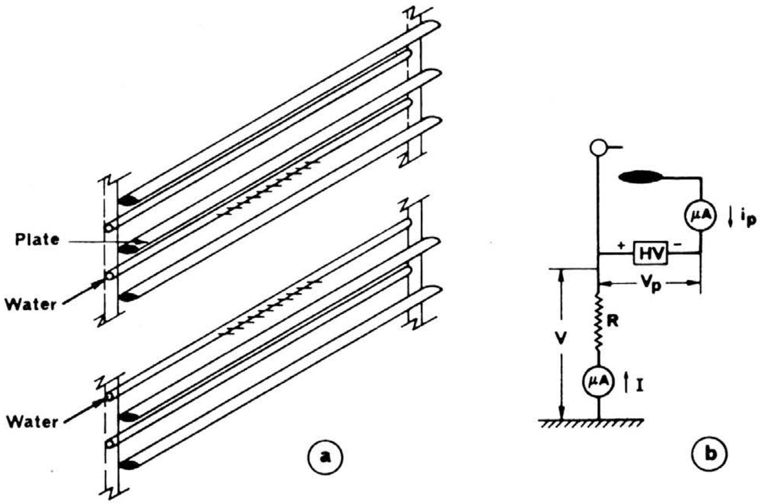

FIG. 6. a) Partial schematic representation of first grid of EFD conversion test set-up. b) Circuit diagram of set-up.

A part of the positively charged droplets are transported toward the collecting grid, giving a useful current I of 1.2 μA. The voltage developed at the terminals of the loading resistor is 25,300 volts and the gross electrical power furnished by the system is 30.36 mW.

The rest of the droplets are picked up by the plates ($i = 1.8$ μA) so that the power used in the aerosol production circuit is 7.2 mW. The power which would be required to pump water in a real generator located 25 meters above the ground is 0.3 mW. Finally, the net power is about 22.8 mW.

This corresponds to a net power density of 1.9 watts/m^2.

It should be noted that the mobility of the droplets calculated on the basis of Vonnegut's law is at least 2.7×10^{-5} m^2/V−s. For this value the one-dimensional theory indicates, for $U = 9$ m/s, a maximum power density of less than 1.5 W/m^2. The fact that the net power density obtained in our experiments is higher is only partially explained by two-dimensional effects favorable to small-surface models. It is also due to the fact that, under our experimental conditions, the emitters produce droplets of different mobilities. The particles of higher mobility are picked up by the plates of the first grid, and only the particles of lower mobility take part in electrical energy production.

6. Discussion

The preceding results show that it is possible to obtain a positive energy balance by producing charge carriers using the electrohydrodynamic spraying method. Energy conversion efficiency is, however, too low to be of practical value.

To improve the efficiency it would be necessary to reduce the mobility of the droplets. This could be achieved by running the aerosol into the unipolar ionized zone of a corona discharge. However, the reduction in mobility must necessarily be compensated by an increase in the number of charge carriers in order to conserve an electric current of sufficient intensity.

To these charge and production rate conditions are added those relative to droplet size. If the droplet radius is greater than 10 microns or so, the power required for water pumping up to the spraying system can exceed the recoverable energy. If the radius is smaller than a micron, the droplets are liable to evaporate before having gone completely through the conversion space [13].

Various expedients [6, 8] would make it possible to extend the range of possible droplet sizes, but they would significantly complicate the contruction of an EFD converter and would consequently reduce its advantages. We think that the solution to the problem of obtaining a suitable aerosol should probably be sought in a combination of two methods:

The EHD spraying method, which is able to furnish droplets a few microns in diameter with a high production rate and a low energy cost.

The corona charging method which, failing the availability of a more convenient method, is capable of affording a favorable modification of droplet mobility.

7. Conclusion

Compared with conventional wind power systems, EFD generators offer certain specific advantages: they do not include moving parts and would make it possible to equip very large surfaces at a relatively low cost. Their operation requires charged aerosols with well-defined properties, whose production using small energy appears difficult.

We have obtained a positive energy balance on a small surface model using an electrohydrodynamic spraying method. However, the power density obtained is low owing to the excessive electrical mobility of the droplets. Considerable progress is still required in order to achieve practical implementation.

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