E-WAter
Official Publication of the European Water Association (EWA)
© EWA 2010 ISSN 1994-8549

Obtaining fresh water from atmosphere using electrostatic precipitation: theory, efficiency and limitations

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***Abstract*—**Efficiency of electrostatic precipitation of water from air is theoretically analyzed in the paper and inherent limitations are determined. It is shown that water drops below a certain minimum size cannot be extracted from air since they either cannot be charged or their charge is insufficient for precipitation. Values of the minimal and effective radiuses of drops are analytically determined. Enlarging the drops is proposed in order to increase the efficiency of precipitation. Future research considerations are presented and experimental setup parameters are proposed.

***Keywords*—**Electrostatic precipitation, Crown discharge, Fresh water

I. INTRODUCTION

At present, humanity is facing a global shortage of fresh water. About one-third of the world's population lives in countries suffering from moderate-to-high water stress. In these countries the water consumption is more than 10% of all renewable freshwater resources. The global water use is expected to increase by 40% by 2020 to meet the needs of the growing population, industrial development and the expansion of irrigated agriculture [1].

The total volume of water on Earth is about 1400 million km^3, of which 2.5 % (about 35 million km^3), is freshwater. Most freshwater take place in the form of permanent ice or snow, locked up in Antarctica and Greenland, or in deep groundwater aquifers. Lakes, rivers, soil moisture and relatively shallow groundwater basins are the principal sources of water for human use. The usable portion of these sources is only about 200000 km^3 of water - less than 1 % of all freshwater and only 0.01 % of all water on Earth, as shown in Table 1. Moreover, the majority of this available water is located very far from human populations, hence further complicating the issues of water use [2].

The replenishment of freshwater mostly depends on evaporation from the surface of oceans. About 505000 km^3 evaporates from the oceans annually, while another 72000 km^3 evaporates from the land. About 80% of all precipitation (about 458000 km^3/year) falls on the oceans and the remaining 114 000 km^3/year on land. The difference between precipitation on land surfaces and evaporation from those surfaces (approximately 47 000 km^3 annually) is run-off and groundwater recharge [3].

Table 1: Major stocks of freshwater (GEO-3, 2002)

Freshwater Source	Volume (1000 km^3)	% of total water	% of total freshwater
Glaciers, permanent snow cover	24 064	1.74	68.7
Fresh groundwater	10 530	0.76	30.06
Ground ice, permafrost	300	0.022	0.86
Freshwater lakes	91	0.007	0.26
Soil moisture	16.5	0.001	0.05
Atmospheric water vapor	12.9	0.001	0.04
Marshes, wetlands	11.5	0.001	0.03
Rivers	2.12	0.0002	0.006
Incorporated in biota	1.12	0.0001	0.003

As follows from Table 1, the atmospheric moisture is one of available significant freshwater sources. The water content in the atmosphere is about six times larger than in all rivers on Earth. Furthermore, it is replenished up to 45 times over one year on the account of evaporations from the surface of land, seas and oceans.

A number of studies have described the contribution of an electric field to the precipitation of atmospheric moisture. In particular, it was shown that an electric field is capable of causing increased rainfall intensity. A generator of water aerosols that produces almost uniform droplets in the above-micron range was presented by Dayan and Gallily in 1974[4]. The collection efficiency of water droplets under influence of electric forces was studied and the size increase of a charged droplet falling through a cloud of neutral, almost uniform small particles was determined by the same authors [5]. The ability of electric field to influence rains in anomalous conditions, i.e. using warm clouds, was revealed in 2004 by an experimental research of crown discharge influence on the evolution of aerosols dispersion and fog density [6]. A useful capability of static uniform electric fields to clear fogs was studied in depth in [7, 8].

The aim of the present study is to discuss a theoretical possibility of water extraction from air with the aid of static electric field. Principles of electrostatic precipitation are briefly reviewed, followed by quantifying practical limitations. Minimum drop sizes are analytically determined for charging and precipitation. Experimental setup is being built to investigate the proposed method; however experimental results are out of the present paper scope.

The paper is organized as follows. Section II describes the principles of electrostatic precipitation and its limitations are discussed in section III; practical drop size is determined section IV. The manuscript is concluded in Section VII.

II. PRINCIPLES OF ELECTROSTATIC PRECIPITATION

The method of air moisture precipitation comprises three main independent stages:
- Ionization of air molecules,
- Charging of water drops in the air by the ion,
- Precipitation of the water drops using a static electric field.

One of most effective methods of ionization and subsequent charging of the particles in the air is the use of crown (or corona) discharge [9, 10]. This method involves passing the gas in between ionized electrodes. When the atoms or molecules come in contact with the surface of the metal electrodes, they lose or gain a charge subject to the polarity of the electrode. The electric field density has to be as high as a few kVm^{-1} to initiate ionization. Corona discharge is a low energy discharge that produces lower density ionization at the cost of a few megawatts of power.
Corona discharge is used in air purifiers to clean air by ionizing it. Atmospheric corona discharge is an alternative device to the traditional pollution control processes of exhaust fumes especially when pollutants (such as NOx, SOx, COV and soot) are in weak concentration in the flue gas [11].
A large quantity of ions is generated by the electric field of the crown. During the collision of ions with a drop of water, the drop is charged. A change of charge in time of a spherical water drop in the air under the impact of the electric field of the crown is represented [12, 13] by

$$Q(t) = 12\pi\varepsilon_0 E r^2 (\frac{\varepsilon}{\varepsilon+2})(\frac{t}{t+t_0}), \tag{1}$$

where
E - intensity of the electric field, generated by the crown,
r - radius of the drop,
t - charging duration,
t_0 - time constant of charging,
ε_0 - dielectric constant of vacuum,
ε - dielectric constant of the drop.

The repulsive forces of ions increase in proportion to the accumulation of charge on the drop. Charging of a drop comes to an end when the value of the repellent field becomes equal to the maximum value of the attracting field. As a result, maximum charge to which a drop of radius *r* can be charged in the electric field of the crown is equal to

$$Q_m = 12\pi\varepsilon_0 E r^2 (\frac{\varepsilon}{\varepsilon+2}) \tag{2}$$

by letting $t \to \infty$ in (1), as shown in Fig. 1.

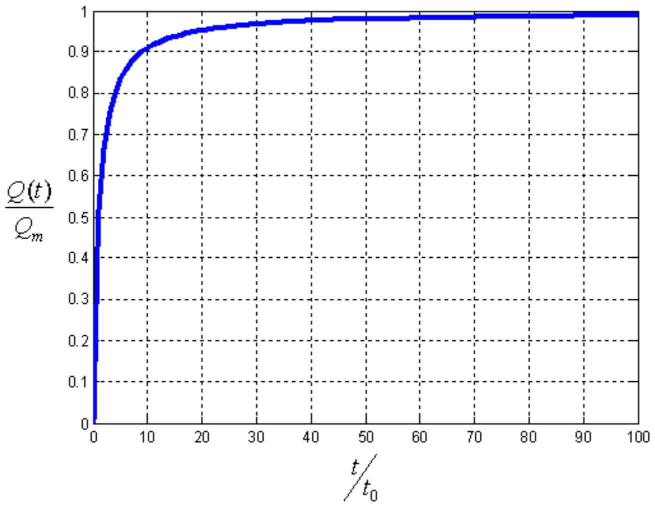

Fig. 1: Drop charge as function of time

Since the charged drop is located in the electric field, it is attracted by the action of Coulomb forces to the electrode with the opposite potential.
The radius of a drop with maximum charge can be determined from (2) as

$$r = \sqrt{\frac{Q_m}{12\pi\varepsilon_0 E}\cdot\frac{\varepsilon+2}{\varepsilon}}\,. \tag{3}$$

Assuming that the maximum possible charge Q_m for a drop equals to the charge of one electron,

$$Q_m = e = 1.6 * 10^{-19} K\,, \tag{4}$$

eq. (3) obtains the following form,

$$r_{\min} = \sqrt{\frac{e}{12\pi\varepsilon_0 E}\cdot\frac{\varepsilon+2}{\varepsilon}}\,, \tag{5}$$

where r_{min} is the radius of the drop with maximum charge equal to the charge of one electron (Fig. 2). Since the charge of one electron is the smallest possible charge, it follows that

a) r_{min} is the minimum radius of a drop, which can be charged in the field of crown;

b) Drops with a radius $r < r_{\min}$ cannot be charged and further extracted from the air using electric field.

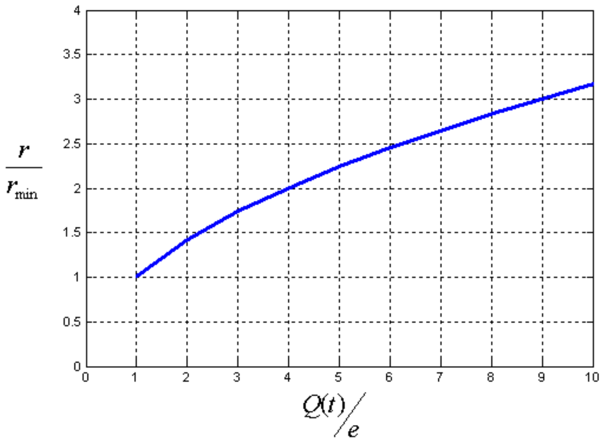

Fig. 2: Drop radius as function of charge

It should be noted that this limitation can be somewhat narrowed by an increase in the electric field intensity. However, a significant intensity increase leads to air breakdown and ignition of electric arc [14].

III. LIMITATIONS OF ELECTROSTATIC PRECIPITATION

Let's examine the behavior of a charged drop in the air influenced by static electric field. Fig. 3 shows the motion of a spherical charged water drop between two electrodes. Let a positively charged drop move evenly with airflow. Applying a constant voltage between the electrodes creates a static electric field with the intensity of *E*.

The following forces act concurrently on the drop:

- Force caused by motion of the air flow F_a. This force compels the drop to move in the direction and with the velocity of the air flow motion.
- Electrostatic (Coulomb) force F_{elec}, directed towards the negative electrode.
- Force of air (hydrodynamic) drag F_s. This force opposes to Coulomb force.

The time of drop lingering in the electric field (between the electrodes) is given by

$$t_a = \frac{L}{V_{air}}, \tag{6}$$

where L is the electrode length and V_{air} is the air (and consequently the drop) speed.

In order the drop to be extracted from the air, it has to reach the negative electrode (subsequently - precipitation electrode) during t_a. If this fails to occur, the drop carried by the air flow will exit the borders of electric field and will not be precipitated.

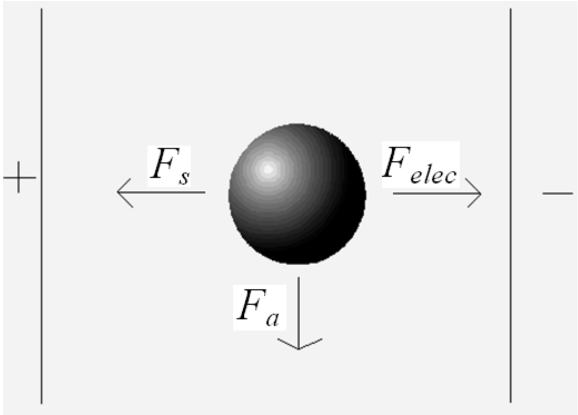

Fig.3: Motion of charged water drop in the electric field

The Coulomb force F_{elec} compels the drop to move towards the precipitating electrode with some acceleration. As the speed of the drop increases, so does the aerodynamic drag force F_s. As soon as the drop velocity reaches some value V_e, the electrostatic and the air resistance forces become balanced,

$$F_{elec} = F_s. \tag{7}$$

From this point, the drop advances toward the precipitation electrode without acceleration with the velocity of V_e. The drop acceleration time to the deposition velocity V_e is short and is usually disregarded. Thus the time of the drop precipitation is given by

$$t_e = \frac{D}{V_e}, \tag{8}$$

where D is the initial distance from the drop to the precipitating electrode.

However, the time of the drop precipitation cannot be longer than the time of drop moving within the borders of the electric field between the electrodes,

$$t_e \le t_a. \tag{9}$$

Hence, combining (6), (8) and (9) determines the lower limit of velocity for a drop precipitation,

$$V_e \ge \frac{DV_{air}}{L}, \tag{10}$$

as shown in Fig. 4.

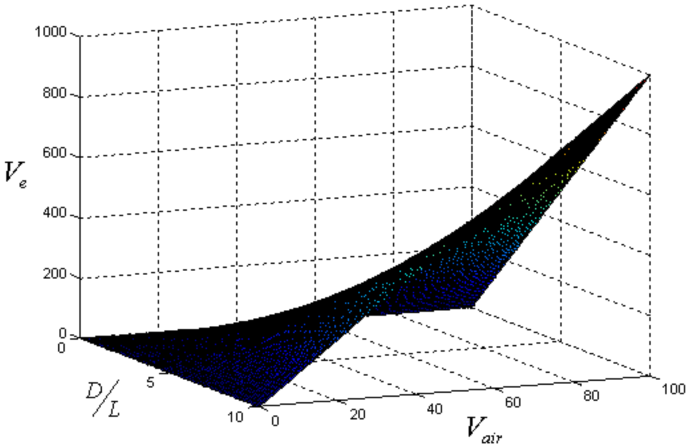

Fig. 4: Velocity limit surface for a drop precipitation

Within the uniform (laminar) airflow, the behavior of the precipitating drop can be determined by using the Coulomb law and the Stokes law. The Coulomb force, propelling the drop is

$$F_{elec} = QE. \tag{11}$$

The force of aerodynamic drag is

$$F_s = \frac{6\pi\mu V_e r}{1 + A(\lambda / r)}, \qquad (12)$$

where

A - dimensionless parameter (for liquid spheres $A \approx 0.86$);

λ - mean free run of the ambient air molecules ($\lambda = 0.942 * 10^{-7} m$ at the pressure of $1{,}013 * 10^5$ Pa and temperature of $25^{O} C$);

μ - viscosity of air ($\mu = 1.837 * 10^{-5} \, {}^{kg}\!/_{m \cdot s}$ at the pressure of $1{,}013 * 10^5$ Pa and temperature of $25^{O} C$).

The Coulomb forces and air resistance are equal when the drop reaches the steady velocity of the drop precipitation V_e. Combining (7), (11) and (12) it is obtained that

$$QE = \frac{6\pi\mu V_e r}{1 + A(\lambda / r)}. \qquad (13)$$

Considering that the drop is charged to its maximum, $Q = Q_m$, and substituting expressions (2) and (10) into (13), it is found that

$$r \geq [(\frac{\mu D V_{air}}{4\varepsilon_0 E^2 L}) * (\frac{\varepsilon + 2}{\varepsilon}) - A\lambda] = r_{eff} \; . \qquad (14)$$

Eq. (14) presents the minimum effective radius r_{eff} for a drop to have in order to be precipitated on the precipitating electrode. Drops with radiuses within $r_{\min} < r < r_{eff}$ can be charged by the electric field of the crown (Fig. 5); however the charge is insufficient for the precipitation during the time of t_e. These drops will be carried beyond the limits of the electric field by the airflow without being precipitated.

Fig. 5: Drop dimensions

IV. DETERMINING PRACTICAL DROP SIZE

For the purpose of minimum theoretical drop size estimation, standard electric field intensity, generated by the crown in the industrial electric air [15] and gases [16] cleaning filters is utilized.

This electric field intensity *E* is usually found within the range of $(30 - 60) \cdot 10^5$ Vm^{-1}. Introducing this typical range of *E* this into (5) results in the range of the possible $r_{\min}$ within the limits of 0.029 – 0.04 µm.

For the purpose of estimation of the minimal size of the drop that could be precipitated on the precipitation electrode, the parameters of the experimental installation being built by the authors, given in Table II, are used.

Table II: Experimental setup parameters

Parameter	Value	Units
D	0.02	m
L	0.3	m
V_{air}	1	m/s
E	500	KV/m
ε	81	N.A.

Introducing the values from Table II into (14), the resulting value of r_{eff} is 0.78µm.

Increasing the length of the electrode and the field intensity or decreasing the cross-section of the air flow as well as air velocity makes possible to precipitate drops with a radius several times smaller than the resultant one. For example, increasing the length of electrodes up to 1,5m, r_{eff} reduces to 0.091 µm.

V. CONCLUSIONS

The proposed electrostatic precipitation method allows partial precipitation of the moisture content only:

1) Water drop of radius smaller than $r_{\min}$ can not be charged in the field of the crown,

2) The charge of water drops of radius smaller than r_{eff} is insufficient for the precipitation.

Hence, the electrostatic precipitation method is effective only in the presence of relatively large drops in the air. The limit imposed by r_{eff} can be somewhat disproved by optimal selection of the precipitation parameters. Alternatively, water drops with radius smaller than r_{eff} can be enlarged before using the proposed electrostatic precipitation method.

This paper takes a realistic approach and shows that there are several limitations to the technology. The usefulness of the process should be yet proved, but with the shortage of water in some parts of the world it is understandable that every approach should be tried.

The paper assumes that the water in the water vapor in the atmosphere and as the liquid water produced by electrostatic precipitation is totally pure. This may be true for the water produced but may not be true for the water vapor in the atmosphere where particulates and dissolved impurities will be present. The effect they will play on the electrostatic precipitation process needs to be considered in the future research. If it does have an effect, then it could alter some of the conclusions reached. With the costs involved with the electrostatic process it will probably only be viable in energy rich countries, for example, in the Middle East where there are deserts and naturally sand particles in the air. In addition, a discussion as to the potential environmental implications of electrostatic precipitation should be made in a future research, which must be a major consideration in this field

Experimental setup (which is a complicated issue by itself) is being built to validate the proposed method. Experimental results are out of the present paper scope and will be reported in a separate paper.

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