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Article

On Prevention and Treatment of Warm Fog on Highways with the Help of Spatially Inhomogeneous Electric Field

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Abstract: A few potential techniques to prevent and disperse warm fogs on highways are discussed. Among these are those based on a net as it is, and also on the combination of net and high voltage electrodes for corona discharge. As a perspective technique, presented is the use of the spatially inhomogeneous electric field for fog dispersion. Our ultimate goal is to propose the fog dispersion technical means based on the use of such a field. In this technique, the electric force acts on droplets directly (via droplet's dipole moment but not via droplet's electric charge) without the intermediate stage of air ionization by corona discharge and droplet's charging. The advantage is that the electric field energy is directly exploited to remove fog droplets from controlled space; there is no energy waste to generate the corona discharge. The described techniques are patented in Russia. On the first step, our methodology includes laboratory experiments. In our laboratory-scale plant, we explore the use of spatially inhomogeneous electric field as a potential technique for warm fog dispersion. In the experiments, the fog, naturally dispersing during half an hour, becomes much more transparent 10 s after the electrode (40 mm in diameter situated in the chamber center) was supplied with the high voltage of 30 kV. The fog is completely dispersed 50 s after the high voltage was turned on. These first results look promising for future efforts to create technical means of fog dispersion via inhomogeneous electric field.

Keywords: Highway; Warm Fog Dispersion; Net; Corona Discharge; Inhomogeneous Electric Field; Lay-Out Diagram

1. Introduction

Fog is a natural weather dependent phenomenon, which causes the reduction of visibility. It consists of water droplets suspended near and above the ground. On highways, a fog, especially dense one, leads sometimes to man-caused disasters: severe damages and traffic accidents. In contrast to traffic damages under clear weather, the damages in fog lead to more serious traffic accidents (**Figure 1**) [1]. Among the damages, there are collisions from behind on highways and head-on collisions on the roads without demarcation strip.

Figure 1. The Damage on the Road Due to Fog in China [1].

Traffic accidents in fog lead to permanent injuries under any lighting conditions: 25 among 1000 fog accidents were registered as lethal compared to lethal 15 among 1000 snow accidents. In the work by Hamilton et al. [2], presented is a descriptive analysis of 23 years fog related fatal crashes and fog related police-reported crashes (1990–2012) from the National Highway Traffic Safety Administration's Fatality Analysis Reporting System and of 19 years of data (1990–2008) from the National Automotive Sampling System General Estimates System. The highest percentage of fog crashes are in New England, in the central US, and in the Pacific Northwest. Fatal crashes involving fog are most prevalent during winter months (December–February) in the overnight (midnight – 5:59 AM) and morning (6:00–11:59) hours. For pileups involving 10 or more vehicles fog is coded in nearly one-in-five occurrences. The main tool to prevent the damages in the fog is the deceleration of car's speed, but usually drivers decrease the speed only when the visibility becomes less than 50 m [3–6]. Therefore various techniques of fog dispersion remain urgent.

Among potential means, we do not consider fog heating to evaporate water droplets (FIDO project [7], for example) which requires heavy energy consumption. During World War II, Royal Air Force exploited such a technology: they burned more than 100 L of fuel per second near the landing strip, and this way they dispersed the fog.

The other dispersion techniques can be divided into two main groups. The first is the fog displacement by the dry air stream to remove the low and cold strata of the atmosphere where the fog takes place [8–10]. To dry the air, these include the use of the precipitator with net and the mechanical drip pan as well. However, the techniques of this group are strongly affected by external environment such as the ambient wind velocity picture. Also, it is a technical problem to form wide stream of dry air or to scan the wide area with narrower stream. One should displace many such machines along the highway and organize the maintenance as well. The second group contains the techniques which use the corona discharge to charge the droplets; electrically charged droplets coalescence more frequently, so that the fog falls to the ground [11–20]. The techniques of this group are more efficient because they inject the charge into moisture and enhance the ability of the droplets to coalescence, but the energy consumption to create the corona discharge remains still significant. To apply the techniques of this group, the corresponding machines should be displaced along the interested section of the road on the windward side which is not always possible. At the same time, its effective use depends on the temporal variations of wind direction. Also, the safe exploitation of corona discharge-based machines looks difficult in the field.

We have found a few publications devoted specifically to the highway (the USA, Italy, and Japan) fog control [21–23]. Also, a systematic safety analysis framework for selecting fog-crash-prone areas on highways was proposed [24].

However, the known physical effect of the spatially inhomogeneous electric field influence on aerosol remains beyond the scope of fog dispersion applications.

The ultimate goal of this paper is to propose a pattern of technical means of the fog dispersion based on the use of such a field. The paper includes six chapters. "Introduction" devoted to the actuality of the problem, "Net Along with Corona Discharge" where the physics of the fog dispersion with the help of nets and corona discharge as well as corresponding technical means are described. "Fog Dispersion by Applying Spatially Inhomogeneous Electric Field" in which the physics, results of laboratory experiments, and potential applications of spatially inhomogeneous electric field to the fog dispersion are presented. "Discussion" reiterates the limitations of existing methods (e.g., energy intensity of corona discharge, weather dependence of air displacement methods) and highlights the advantages of the proposed electric field method. This section makes a strong case for the innovation's efficiency and feasibility. "Conclusions" effectively summarizes the three approaches discussed and reiterates the superiority of the spatially inhomogeneous electric field technique. It aligns with the paper's narrative and findings.

There are several types of fog. Below, we consider the dispersion of warm fog only.

2. Net Along with Corona Discharge

Physics of the fog dispersion with the help of nets is as follows. Droplets of fog touch the flat net, accumulate on its wires, and flow downward, while remaining dry air flows downwind. Let us emphasize that such a construction separates only droplets that touch the net. However, aerodynamic forces (proportional to the second power of droplet's radius), acting on the droplet, are much stronger than droplet's inertia (proportional to the third power of droplet's radius):

$$k = \frac{F_v}{F_i} = \frac{k_1 r^2}{k_2 r^3} = \frac{k_1}{k_2 r} \qquad (1)$$

Here F_v – aerodynamic force; F_i– inertial force; r – droplet's radius; k, k_1, k_2 – constants.

For a small droplet, $r \to 0$, so that $k \to \infty$. Thus, small droplets flow around an obstacle practically along foggy air streamlines. Taking into account the low foggy air velocity through the net and the small water droplet size, one can apply the Stocks criterion to estimate the possibility of collisions of droplets with net and, hence, the effectiveness of water collection:

$$S_{tk} = \frac{\lambda}{2R} = \frac{\rho \overline{\omega}_0 d^2}{18\mu 2R} \qquad (2)$$

Here λ – droplet's inertia path in the air; R – radius of mesh's wire; ρ – water density; $\overline{\omega}_0$ – velocity of incident flow; d – droplet's diameter; μ – air dynamic viscosity.

Under small Stocks numbers S_{tk} typical for the droplets of small size and mass, the droplets follow streamlines of foggy air [12]. To increase the possibility of collisions of water droplets with net's wires one should enhance the Stocks number. For the given spectrum of droplet's scales, the adjustable parameters are the net's wire diameter and the velocity of incident flow. The smaller is the wire diameter the higher is the Stocks number, and the higher is the probability of collisions. The lay-out diagram of a machine realizing this principle of the droplet collection is patented in Russia [25]. The cleaning of the foggy air from fog's droplets is realized by pushing the air through the porous material by the overpressure. The machine contains waterproofing plates installed one above another at an angle to horizon with the porous material between them. The porous material is the steel wire (no more than 1 mm thickness) made. Most of the wires are orientated vertically so that the water collected on the wires will trickle down. This helps to increase the number of wires without the decrease of the area available for the foggy air stream. To increase the effectiveness of cleaning, one ought to increase the velocity of incident flow ($\overline{\omega}_0$). In other words, one should move the net relative to the foggy air stream. The motion of the assembly with porous material inside is realized in the plane crossing the foggy air flow direction. The assembly with porous material can be realized as the two disk fragments fastened on fan's vanes. Droplets collide with the steel wool, stick to wool's wires, and separated this way from the foggy air stream. The centrifugal force moves the droplets along the wires to outer parts of the fan. The speed of the fan's vane motion summarizes with the velocity of the foggy air, and this allows precipitating the droplets of any given scale: due to the coalescence the droplets become larger, and when centrifugal force overwhelms the capillary force, the enlarged droplets throw out to periphery. The foggy air velocity in relation to the porous material, which determines the probability of collisions of droplets with steel wool, is depended on the angular velocity of fan's vanes. Increasing the fan rotary speed, one can achieve any arbitrary given separation efficiency. The lay-out diagrams of machines realizing this principle of the droplet collection are patented in Russia [26,27]. For applications, one should choose the largest fan presented on the market (in Russia, typical sample size is 630 mm in diameter). The replication looks difficult because it depends on meteorology and, in particular, on the highway orography.

Another way to increase the effectiveness of water collection is the use of additional electric means close to the net [28].

As an additional electric means, one applies high voltage to the corona discharge electrodes mounted close to the net (**Figure 2**). Fog water droplets, passing through the corona discharge area (forming around the electrodes), get electric charges. Electrically charged droplets are attracted to grounded net's wires due to electric forces. Hence, when the foggy air passes through the corona discharge area before, the electrically charged droplets will be removed more effectively. In this case, the porous material could be electrically grounded steel wool, and this increases the effectivity of water collection without the increase of net's aerodynamic drag.

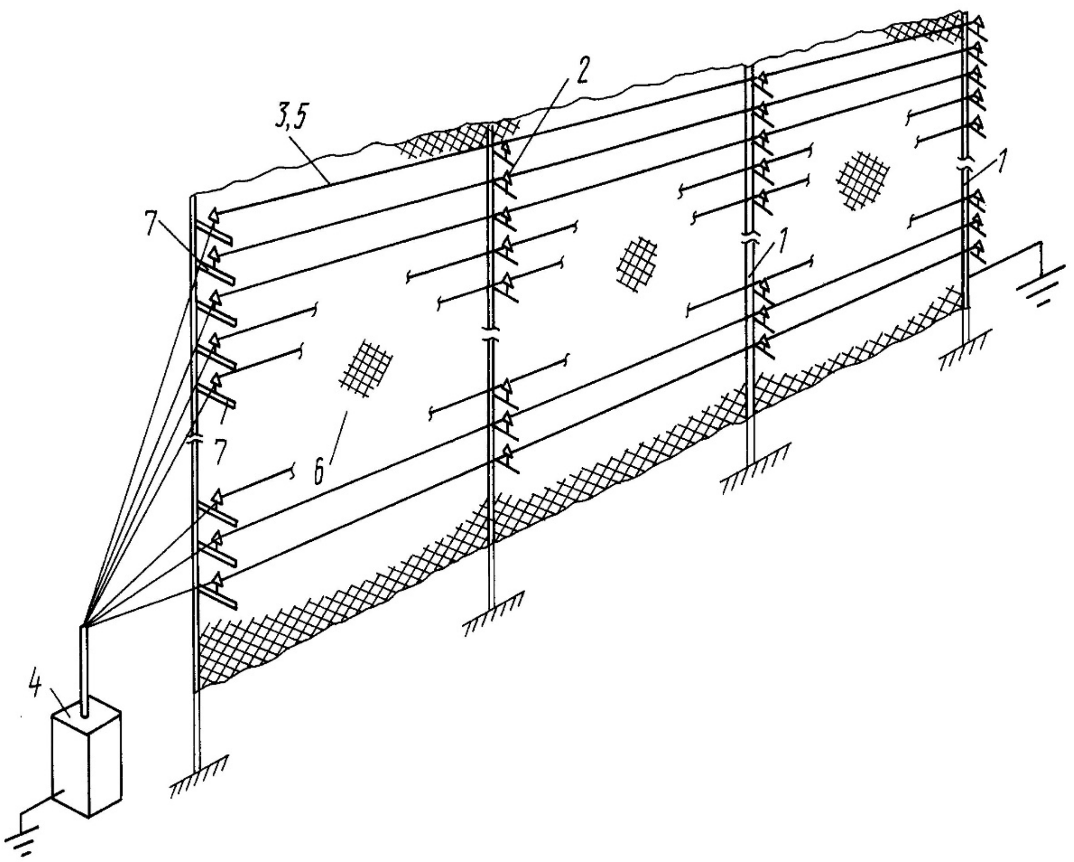

Figure 2. Lay-Out Diagram [28]: 1 – Supports; 2 – Insulators; 3, 5 – Corona Discharge Electrodes; 4 – High Voltage Power Supply; 6 – Grounded Net; 7 – The Insulator.

A machine includes grounded conducted net, mounted as a fence along roadbed on windward side of fog's flow. High voltage insulators are installed in pairs on net's supports. Corona discharge electrodes connected to high voltage supply are mounted vertically with a gap in the relation to the grounded net. To ensure the guaranteed gap, collecting electrodes are vertically mounted equidistantly with the step equal to the step between coronal discharge electrodes. This is needed to ensure gap's accuracy over the whole net area. The effectiveness of a machine is determined mainly by the ion wind velocity. The latter achieves its maximal value in case of maximal possible discharge's electric current. The longer is the gap the smaller is the electric current, and the smaller is the effectiveness. When the gap decreases, electric breakdown is possible, and a machine shuts down. In windy environments, one should ensure the stable gap over the whole area of grounded net.

The machine operates as follows. When the high voltage is supplied to corona discharge electrodes, the strong electric field between these and collecting electrodes ignites the corona discharge, and the ion wind directed from corona discharge electrodes to collecting ones is created. Its velocity is proportional to the square root of discharge's electric current. The ion wind moves the air with fog's droplets to collecting electrodes through the area of corona discharge, where the droplets acquire the electric charge. Electrically charged droplets deposit on grounded net more frequently than electrically neutral ones. Cleaned from droplets air is directed to the foggy region and forces out the fog. Stable burning of the corona discharge determines the high effectiveness of the machine. The ion wind velocity in the field experimental machine construction was of the order of one meter per second.

The machine of fog dispersion with the net of 70% transparency (the ratio of a mesh area to net's general area) ensures the effectiveness of water collection no less than 85%: under the action of ion wind, the residual optical density, that makes 15% of the original one, may mean that the droplet capture coefficient is equal to 0.85 [29]. The ion wind created in corona discharge area and directed from the electrodes to grounded net's wires along electric field lines helps the fog to move through the net. The machine does not create additional aerodynamic drag, and, moreover, involves the fog inside. The photo of the machine is presented in **Figure 3**. Concerning the replication, it can be assembled from separate modules: there are five such modules (3 m in height and 2 m in length each) in **Figure 3**.

Figure 3. A Machine to Disperse Fog: 1 – High Voltage Insulator; 2 – High Voltage Power Supply; 3 – Grounded Electrodes; 4 – Corona Forming Electrodes.

We have conducted preliminary field tests of the pre-production model (10 m length, 2.5 m height) of the machine assembled at Nalchik airport (Northern Caucasia, Russia). Our goal was to evaluate its effectiveness and to specify the details of the process in real atmospheric conditions. The action of the machine (**Figure 4**) is illustrated by **Figure 4a,b**. The fog was dispersed downwind during one minute, while it lasts stable during two hours before the machine was turned on.

Figure 4. Fog Dispersion One Minute After a Machine was Turned on. (**a**) The Beginning of Fog Dispersion; (**b**) 60 s after a Machine Was Turned on.

Very limited number of field experiments in Nalchik airport does not allow estimating error margins statistically. Despite high efficiency, the above considered techniques can only be realized on stationary mounted equipment to protect highway sectors of high creation probability of long lived fog. A lay-out diagram of the development of a highway with the help of these machines installed along the roadbed is presented in **Figure 5**.

Figure 5. Lay-Out Diagram of Highway Development: 1 – The Fog Dispersion Machine; 2 – Roadbed.

The machine can disperse fog over the whole width of the road, but its action is effective downwind only. Another limitation is that the foggy air velocity should be no more than 4 m per second; otherwise, the effectiveness of a machine decreases – no more than 20% of droplets are separated under the velocity higher than 4 m per second.

3. Fog Dispersion by Applying Spatially Inhomogeneous Electric Field

Physics of the fog dispersion by applying spatially inhomogeneous electric field is as follows. Water droplets of the fog are polarized in the electric field so that its electric dipole moment will ensure its motion in the direction of enhancing gradient of the field electric energy under the action of Helmholtz's force [30]:

$$\vec{f} = \frac{\varepsilon - 1}{8\pi}\vec{\nabla}E^2 \tag{3}$$

Here, ε — water vaper dielectric permittivity; E — electric field strength.

Because the air dielectric permittivity is close to unit, one can neglect the Helmholtz force action on the air. Hence, the electric force acts only on droplets and acts directly (via droplet's dipole moment but not via droplet's electric charge) without the intermediate stage of air ionization by corona discharge and droplet's charging. The advantage of the use of the spatially inhomogeneous electric field for fog dispersion is that the electric field energy is directly exploited to remove fog droplets from controlled space; there is no energy waste to generate the corona discharge.

We have explored the effect using our laboratory-scale plant. The plant described in the work of Alekseeva et al. (**Figure 6**) contains the technical unit 1, made as metal frame with the fog chamber installed on its support platform [31].

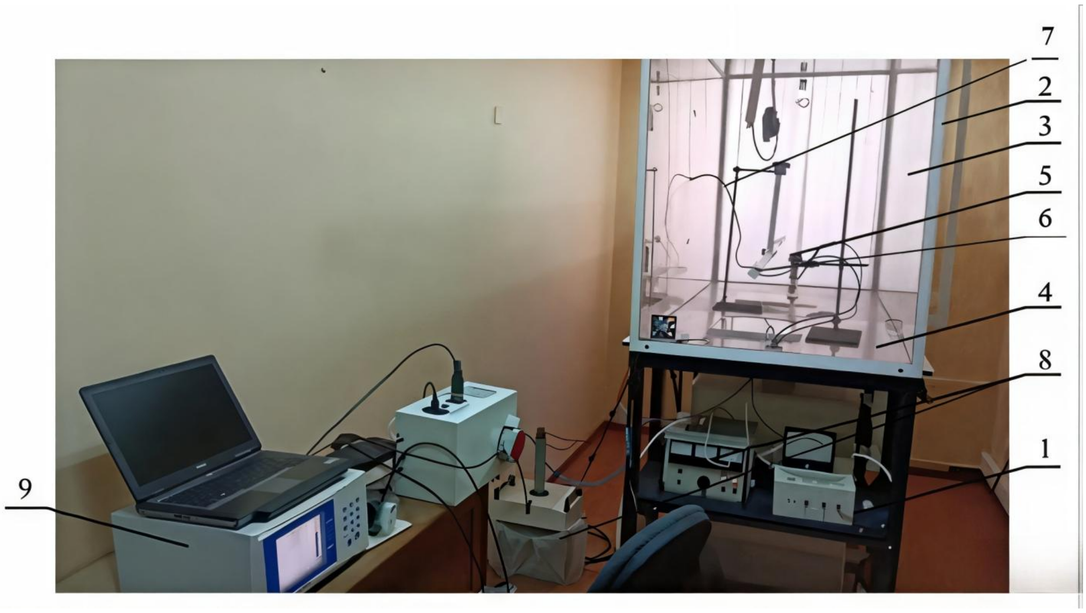

Figure 6. The General View of the Laboratory-Scale Plant to Explore the Inhomogeneous Electric Field Influence on Fog Dispersion: 1 – Technical Unit; 2 – Fog Chamber; 3 – Fog Chamber Sidewalls; 4 – Fog Chamber Bottom; 5 – Moisture Feeding Unit; 6 – Inhomogeneous Electric Field Formation Unit; 7 – High Voltage Cable; 8 – High Voltage Power Supply; 9 – Measuring Equipment.

The fog chamber (2 × 0.8 × 1.3 m) has the aluminium frame 2, and its sidewalls are transparent polycarbonate sheets 3. The fog chamber bottom 4 made from aluminium alloy has the cooling and grounding systems. In the chamber underbody, moisture feeding unit 5 is installed, which is connected with the fog creation system (installed in the technical unit) by pipe duct. Nearby the moisture feeding unit, the model of inhomogeneous electric field formation unit 6 is installed. We use the АИД-70 device as high voltage power supply, which has up to 70 kV working voltage, and up to 12 mA working electric current.

In experiments, we create the spatially inhomogeneous electric field in the fog with the help of the high voltage supplied electrode installed in the fog chamber fulfilled with moisture. The moisture is formed with the help of ultrasonic air saturator "Boneco", whose working principle is based on membrane ultrasonic vibrations. Under the membrane action, the moisture is formed, and it is directed into the fog chamber with the help of the feeding unit. Due to chamber bottom cooling, this moisture creates the fog in chamber's underbody. The fog remains stable and does not naturally disperse during more than 20 min. We use a polypropylene tube 40 mm in diameter armored with aluminium envelope (PP-ALUX PN 32, VTp.700.AL25.32). We supply the aluminium envelope with high voltage from the high voltage power supply by high voltage cable through the blank flange hermetically mounted on tube end surface. The opposite tube end is also insulated with hermetic blank flange. So, the high voltage electrode is the thin aluminium envelope whose hermetic insulation eliminates leakage currents on its surface. Dielectric characteristics of polypropylene, encompassing the envelope, ensure the insulation of the electrode up to the voltages of 50 kV DC.

The fog, naturally dispersing during half an hour, becomes much more transparent 10 s after the electrode (40 mm in diameter situated in the chamber center) was supplied with the high voltage of 30 kV. The fog is completely dispersed 50 s after the high voltage was turned on. The dynamics of fog dispersion is presented in **Figure 7**.

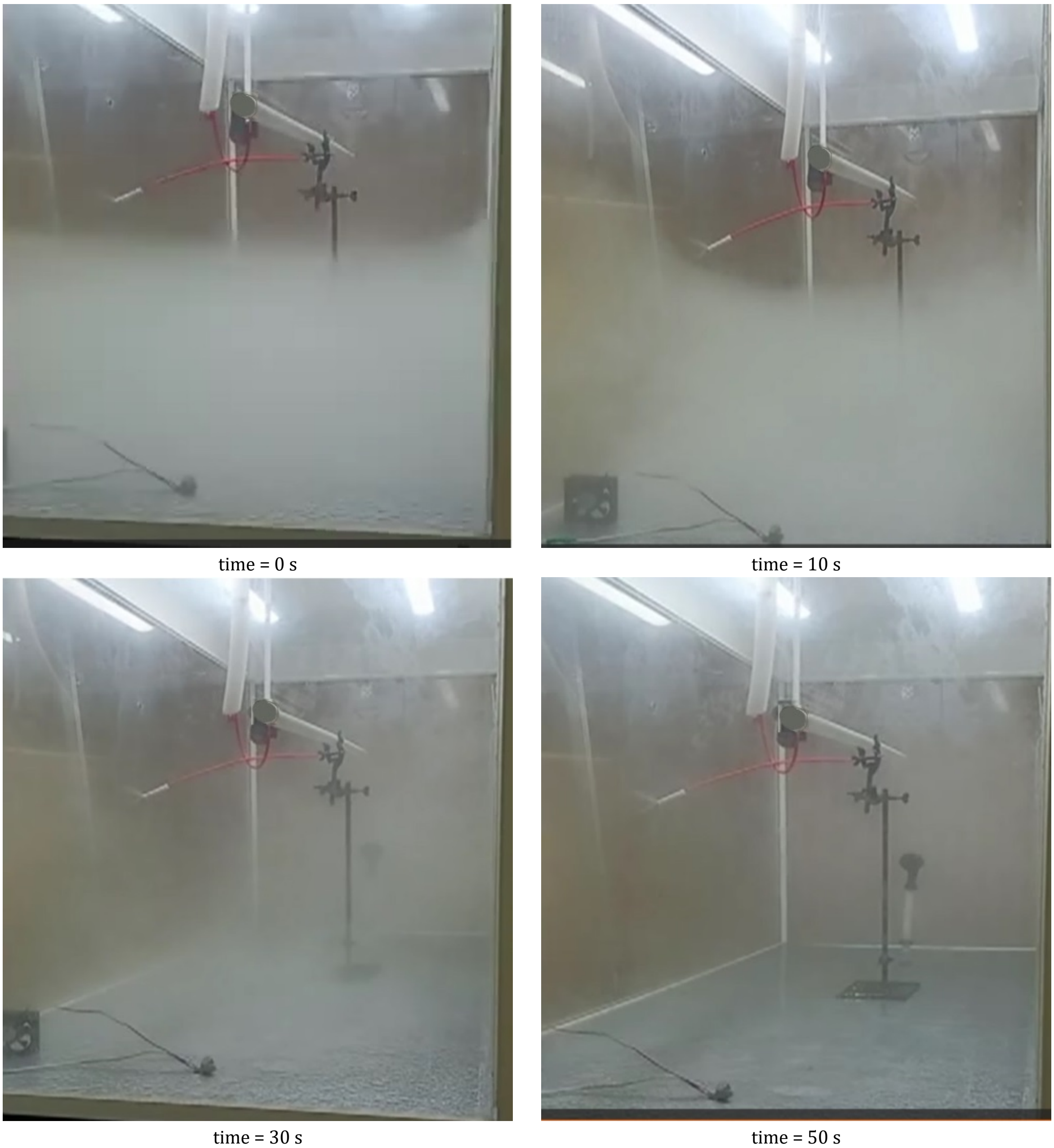

Figure 7. The Dynamics of Fog Dispersion by Inhomogeneous Electric Field.

The stronger is the high voltage the faster is the fog dispersion. Energetic consumption of the process is negligible: the supply of the electrode of 40 mm in diameter and 1200 mm in length with the high voltage of 30 kV creates the electric current value of 0.15 μA. In the future, we will add our fog chamber with a medium-phase two-way transmissometer based on the helium-neon laser with the wavelength of 0.63 μm to estimate the effect quantitatively.

When one exploits the effect of spatially inhomogeneous electric field to disperse fog, the lay-out diagram of the development of highway becomes simpler (**Figure 8**) [32]. In this case, there is no need in the hang-the-expense approach with the installation of energetically consumable corona discharge electrodes on both sides along the highway (**Figure 5**): strong spatially inhomogeneous electric field can be created by special electrode mounted above the highway as it is presented in **Figure 8** [32]. A machine disperses the fog by the influence of the spatially inhomogeneous electric field. An element of the machine is the smooth cylinder electrically conducting envelope no less than 15 mm in diameter. Each element has electric connectors mounted on envelope's flanks. The lateral surface of the envelope is covered with insulating material. This design protects from high voltage generated leakage currents on connections between the elements of the machine. The diameter of an electric connector should be no more than the diameter of the cylinder envelope. The long electric cable assembled from the described elements fastened to steel ropes, which mounted on supports via high voltage insulators along a roadbed. Hence, the machine is reproducible.

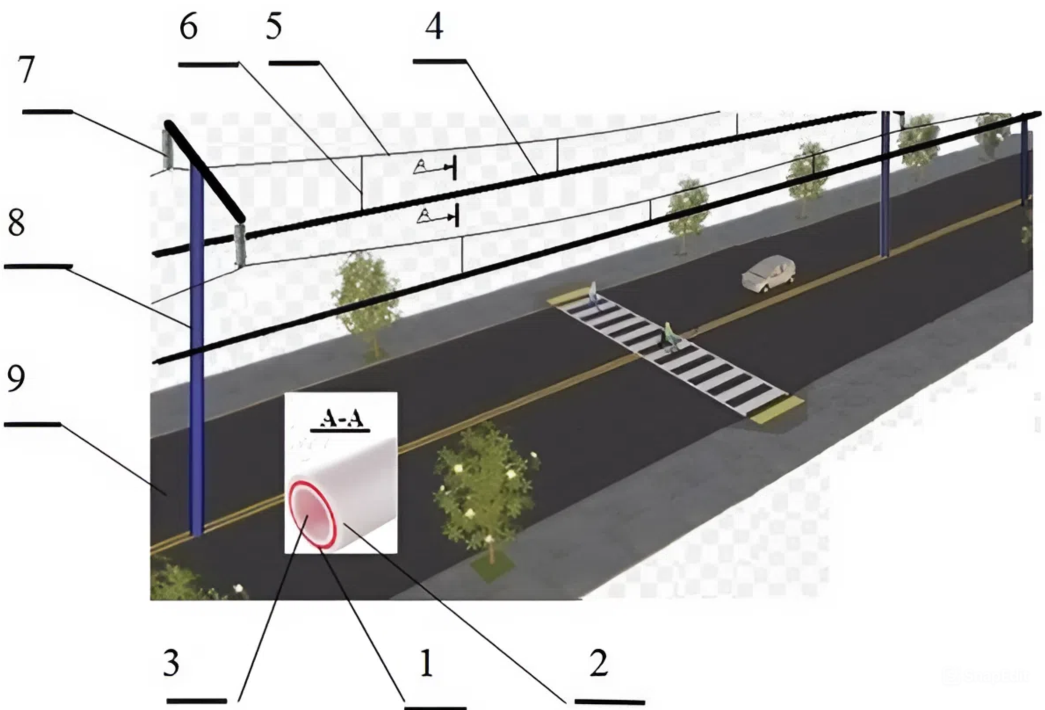

Figure 8. Lay-Out Diagram of Highway Development to Disperse Fog by Inhomogeneous Electric Field [32]: 1 – High Voltage Electrode; 2 – Outer Insulation of the Electrode; 3 – inner insulation of the electrode; 4 – High Voltage Electrode; 5 – Steel Rope; 6 – Bracket of the Electrode; 7 – High Voltage Insulator; 8 – High Voltage Support; 9 – Roadbed.

The machine can disperse fog over the whole width of the road, but the spatial reach strongly depends on both the high voltage value and the wind velocity and direction.

4. Discussion

On highways, a fog can lead sometimes to man-caused disasters: serious damages and traffic accidents. So there is no doubt that actual is the development of variety of fog dispersion methods.

The fog occurs in the form of supercooled one or in the form of warm one. One can disperse supercooled fogs by spraying special reagents (argentum iodine, calcium chloride, artificial ice, etc.). The reagents initiate the destruction of thermodynamic equilibrium taking place in the fog. To deliver the reagents, airplanes, missiles, and shells are used.

However, warm fogs are thermodynamically stable so that the reagents will not disperse them. To disperse warm fogs, one can, for example, displace the fog by the dry air stream to remove the low and cold strata of the atmosphere where the fog takes place [8–10]. At the same time, such techniques are strongly affected by external environment such as the ambient wind velocity picture. Also, there exist techniques that use the corona discharge to charge the droplets; electrically charged droplets coalescence more frequently, so that the fog will fall to the ground [11–20]. The apparatus includes wires of small diameter connected to high voltage supply. These techniques are more efficient because they inject the charge into moisture and enhance the ability of the droplets to coalescence, but the energy consumption to create the corona discharge remains still significant. The effectiveness of the corona discharge-based machines is limited to relatively low ion wind velocity value, which is determined by the value of the electric current in the corona discharge. The fog can be effectively dispersed downwind only. In calm weather the apparatus disperses the fog in a short distance, which is determined by the low ion wind velocity (2 m per second maximum).

A perspective technique that we propose is the use of the spatially inhomogeneous electric field for fog dispersion. In this technique, the electric force acts on droplets directly (via droplet's dipole moment but not via droplet's electric charge) without the intermediate stage of air ionization by corona discharge and droplet's charging. The advantage is that the electric field energy is directly exploited to remove fog droplets from controlled space; there is no energy waste to generate the corona discharge. In this case, the lay-out diagram of the development of highway becomes simpler: there is no need in the hang-the-expense approach with the installation of energetically consumable corona discharge electrodes on both sides along the highway: strong spatially inhomogeneous electric field can be created by special electrode mounted above the highway. We highlight this new technique as a perspective direction of future research in the area of warm fog dispersion [32]. The safety of the machine realizing this new technique is ensured by special patented means of separate modules; the modules are not exposed to the influence of environment, including weather conditions [32]. Because the high voltage cable should be manufactured from highly electrically isolated patented modules, there is no potential risk connected to exposure to high voltage. The machine needs no maintenance.

The feasibility of implementing the developed technique in real world can be tested in specially organized field experiment. The possible field experiment to disperse the fog above the highway with the help of spatially inhomogeneous electric field is directed to test the effectiveness of this technique in real exploitation conditions.

In the experiment, obtaining space-time characteristics of the fog dispersion process and determining their dependences on design and electric parameters of the system of spatially inhomogeneous electric field formation (including geometrical and design peculiarities of high voltage electrode, the value of high voltage supplying the electrode, disposition of high voltage electrodes along the highway, etc.) will be the first objective. The second objective will be investigating the meteorological conditions influence (including the direction and velocity of fog's flow to highway, the air temperature, the aerosol spectrum, the electric field strength, the air electric conductivity, etc.).

The experiment is planned on the kilometer length highway section divided into four parts 250 m length each. The section should be chosen in the place, where the fog moves mainly perpendicular to the highway. On the section, there should be lampposts. The adjoining area (250 m from the section on both sides) should be free and accessible for scientific measurements.

On each of four parts of the section, high voltage electrodes of one of four chosen different external diameters should be mounted. In the experiment, aluminium armored polypropylene tubes (such as VTp.700.AL25.90, VTp.700.AL25.75, VTp.700.AL25.63, and VTp.700.AL25.50 of four different external diameters widely presented at the market) could be used. The listed tubes should be modified in accordance with Ru225701U1 patent.

Scientific devices needed include: fog density meters; air temperature, humidity, and speed and direction meters; aerosol spectrometers; electric field strength meters and air electric conductivity meters. Our estimate of the expenses to conduct the experiment is $180,000 per kilometer, and it is approximately three times lower than the expenses to conduct the similar experiment with net based machines.

5. Conclusions

Several potential techniques for warm fog dispersion on highways are described and analyzed.

In precipitators with nets, two improvements are proposed. The first is to decrease the net's wire diameter. The second is to move the net relative to the foggy air stream increasing this way the velocity of incident flow. The lay-out diagrams of machines realizing these ideas of the droplet collection are patented in Russia [26,27].

One can increase the effectiveness of fog dispersion by applying high voltage to the corona discharge electrodes mounted close to the net. Fog water droplets, passing through the corona discharge area (forming around the electrodes), get electric charges. Electrically charged droplets are attracted to grounded net's wires due to electric forces. The ion wind created in corona discharge area and directed from the electrodes to grounded net's wires along electric field lines helps the fog to move through the net. A machine does not create additional aerodynamic drag, and, moreover, involves the fog inside. It is patented in Russia [28].

In our laboratory-scale plant, we explore the use of spatially inhomogeneous electric field as a potential technique for warm fog dispersion. Water droplets of the fog are polarized in the electric field so that its electric dipole moment will ensure its motion in the direction of enhancing gradient of the field electric energy under the action of Helmholtz's force. In this effect, the electric force acts on droplets directly (via droplet's dipole moment but not via droplet's electric charge) without the intermediate stage of air ionization by corona discharge and droplet's charging. The advantage of the use of the spatially inhomogeneous electric field for fog dispersion is that the electric field energy is directly exploited to remove fog droplets from controlled space; there is no energy waste to generate the corona discharge. In the experiments, the fog, naturally dispersing during half an hour, becomes much more transparent 10 s after the electrode (40 mm in diameter situated in the chamber center) was supplied with the high voltage of 30 kV. The fog is completely dispersed 50 s after the high voltage was turned on. In the future, we will add our fog chamber with a medium-phase two-way transmissometer based on the helium-neon laser with the wavelength of 0.63 μm to estimate the effect quantitatively. Organizing the series of experiments to check the technology in field conditions is the next natural step of the technology development. When one exploits the spatially inhomogeneous electric field, the lay-out diagram of the development of highway becomes simpler: there is no need in the hang-the-expense approach with the installation of energetically consumable corona discharge electrodes on both sides along the highway (strong spatially inhomogeneous electric field can be created by special electrode mounted above the highway) [32]. The integration with existing highway infrastructure looks relatively easy: one can hang up high voltage cable above the high way on existing illumination supports. Specific directions for future research include field experiments on one kilometer length part of the road, and, in case of positive results, preparations of proposal of pilot industrial project, in which the potential impact on road safety and infrastructure policy will be clarified. Our estimate of the expenses to conduct the experiment is $180,000 per kilometer, and it is approximately three times lower than the expenses to conduct the similar experiment with net based machines.

6. Patents

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Author Contributions

Conceptualization, A.P.; methodology, A.P.; validation, A.A. and M.Z.; formal analysis, V.D.; investigation, A.A., V.D., A.S., and M.Z.; writing, A.P. and Y.P.; writing – review and editing, Y.P.; supervision, Y.P. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

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Data are available from the authors under request.

Conflicts of Interest

The authors declare no conflict of interest.

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