Quantum effects in electrostatic precipitation of aerosol and dust particles

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Abstract

Well established technology of pollution control by electrostatic precipitation is in essence based on concepts of "classical" physics. At the same time, recent advances in several directions of quantum physics, especially in understanding macroscopic quantum effects, quantum entanglement, quantum coherency and quantum information open additional potentially valuable avenues for possible pollution control applications and electrostatic precipitation in particular. This paper provides an overview of several promising research lines along these less explored routes.
Keywords: electrostatic precipitation, dust particles, quantum effects, nonlocality, quantum entanglement, information theory, Shannon entropy, ergodicity.

1 Introduction

The objective of air cleaning methods such as an electrostatic precipitation (ESP) is to control the dynamics of diluted distributed systems consisting of zillions of small particles suspended in air streams. Hence it is worth looking at these methods from the systemic point of view; the latter means that the emphasis is directed to the connectivity within the distributed system.

The purpose of this article it to overview the connectivity issues in particulate systems (such as aerosols, soots, dusts, etc) with prime attention towards quantum effects. By the necessity such reviews are always somewhat selective and reflect the personal preferences and particular interests of their authors.

Due to space limitations only the most concise description is given. Also, it should be noted that the fast (and still on-going) progress in Web search engines reduces a need for comprehensive bibliographies because most topics and authors can be efficiently searched through key words. This, in a sense, can be seen as an extrapolation of the notorious "Moore's Law" (doubling of computer chip power every two years) to exponential growth of scientific and technological information and advances in computer search tools. Thus, in most cases (and following the tradition of the famous course of Theoretical Physics by Landau and Lifschiz), this article quotes only the names of key authors instead of full references.

2 Aerosol and particulate suspensions as macroscopic quantum systems

To this day experimental, theoretical and computational (modeling) progress in aerosol science and ESP methods is largely based on well established ("classical") areas of physics [1,2]. This includes classical electromagnetism (Maxwell and Laplace equations), plasma discharge phenomena, particle charging, particle dynamics in electric fields, diffusion of aerosol and dust particles in the air flow and statistical physics of dispersed and dusty systems.

From its inception as a separate engineering area almost a century ago, ESP has evolved into a firmly established and important segment of environmental technology. Its applications for air cleaning range from large scale industrial facilities to small ESP for residential furnaces.

Likewise, as an area of research, ESP has generated a sizable theoretical and experimental activity within the general realm of applied electrostatics. Fundamental principles and underlying mechanisms of ESP seem to be relatively well understood.

Thus, an overview of ESP may create an impression that this area is largely "done" and that there is not much can be added to it from the side of novel ideas in quantum physics. Such a view, however, is somewhat superficial and it is the purpose of this article to indicate some unexplored aspects of ESP where the injection of quantum physics may open new and unexpected vistas.

The prime objective of ESP technology is the removal of the particulate particles from the air by means of charging them and subsequent directed motion in the electric fields. Particulate in question typically consists of solid or liquid particles whose size ranges from the fraction of the millimeter to several nanometers. In the case of submicron particles they can be referred to as mesoscopic systems. The latter, as this very term implies, occupy an intermediate position between the macroscopic objects which mostly can be described by classical physics and truly microscopic objects (atomic and molecular size) whose physical behavior to a significant degree obeys the laws of quantum physics. While the boundaries between macroscopic, mesoscopic and microscopic regions are somewhat fuzzy and arbitrary, here we focus the attention primarily on nanoscale particles of 10 to 100 nm (0.01 PM to 0.1 PM). This size range represents a relatively difficult area for ESP and yet the removal of the submicron and nanoscale particulate remains an important and challenging segment of air pollution control technology.

3 Quantum entanglement and quantum non-locality effects

In contrast to such mechanical methods of air cleaning as gravitational settling, filtering and centrifugal separation, ESP invokes particulate charging as a first step of the whole process. One of the key questions here is whether it is critical that each and every individual particle needs to attain its own net electric charge in order to be ESP collected. At first glance, the answer is yes - how else a neutral particle is supposed to be dragged by an electric field to the collection electrode?

However, in quantum physics we can expect a more peculiar situation when neutral particles being elements of a connected quantum system can experience a net force due to their non-electrostatic quantum interactions with charged particles [3]. This way a larger pool of neutral particles can participate is ESP.

One of the characteristic and persistent features of classical (Newtonian) physics is the idea of reductionism, that is the notion that the behavior of a complex system is always explainable and derivable from the behavior of its constituting parts. While presently the questioning of the reductionistic views primarily happens in biology, their limitations are less obvious in physics, the reason being that in physics many effects occuring in large systems were indeed satisfactory explained on the basis of the reductionistic analysis. Thus, reductionism keeps a stronghold in physics. And yet, in some key areas reductionism seemingly is not working well. Examples were it (so far, at least) shows the weakness range from the stability of galaxies to the origins of complexity in chaotic systems. As such, dusty and aerosol systems may also be good candidates for non-reductionistic description.

To give an example, liquid charged droplets are subjected to the Rayleigh stability criterion. Droplets rupture when the total energy of electrostatic repulsion exceeds the energy of the surface tension. An open question is whether the quantum entanglement (quantum connectivity) between smaller droplets persists after the rupture. If quantum entanglement works for quantum particles of atomic sizes, it is not unreasonable to expect that it may also maintain some of its validity for larger (e.g., for nanoscale or even micron size) particles and systems.

3.1 Quantum connectivity and quantum coherency in particulate systems

In spite of their chaotic nature, extended systems of dust particles such as soots or aerosols can be considered as macroscopic quantum systems consisting of particles of mesoscopic size (10 nm to 1000 nm). This is typical size range for such quantum objects as Cooper pairs or quantized orbits in quantum Hall effect.

After the advent of quantum mechanics in 1920-s the word "quantum" was used to generate an ever growing pool of combined 2-word terms such as quantum states, quantum transitions, quantum correlations, quantum coherency, quantum non-locality, quantum logic, quantum computing, etc. Coherency and non-locality are of particular interest in the context of this article. These terms emphasize the unity aspects of the systems consisting of spatially separated parts.

Such collective effects as superconductivity (electronic Cooper pairs in superconductors), superfluidity (quantum vertices), quantum Hall effect (integer and fractional), or establishing of coherency in lasers - all point to the inner interconnectedness in spatially extended systems. While in each case the manifestation of quantum interconnectedness requires specific conditions (e.g., low temperatures), such conditions are usually relatively liberal; often quantum connectedness can dominate the system in-spite of disordering factors (such as thermal randomization, chaotic velocities of particles, etc).

3.2 Charge and energy transfer and precipitation dynamics

Effects of "self-charging" (spontaneous charging) in the systems of dust particles may be due to cases of energy minimization when an asymmetric charge distribution forms an energetically preferable state [4]. The latter refer to the spontaneous charge separation due to polarization effects. In example considered in [4] a symmetrical system of two neutral impurity atoms in a crystal spontaneously goes to an asymmetrical state. An electron moves (by quantum tunneling) from one impurity to another thus creating positive and negative ions. Because of the polarization of the surrounding crystal lattice, the total energy of the system decreases which makes the asymmetric configuration energetically preferable to the symmetric one. Similar effect of the spontaneous symmetry breaking may happen in the system of dust particles leading to the induced charging of the particulate ("self-charging").

For example, the following model system can be of relevance for the said effect of "self-charging". Consider a spherical dust particle and a nearby single ("free") electron. Due to the image charges and the van der Walls interaction effects dust particle and an electron can form a connected system resembling the atomic Rydberg state (state with extended electron orbits).

4 Quasi-stationary electrostatic configurations

4.1 Lifetime and decay of quasi-stationary quantum states

Quasi-stationary states in quantum mechanics refer to those states which form relatively stable configurations but have a finite lifetime instead of existing indefinitely. Example of a quasi-stationary state is a radioactive nucleus (e.g. C-14 isotope) which sooner or later spontaneously decays into another isotope [5]. In systems of dusty charged particles many relatively long lived complexes may form spontaneously. Depending on subtle variations of their configuration their lifetime can be drastically different, allowing for ESP collections in favorable situations (longer lifetimes of quasi-stationary complexes).

4.2 Saddle point effects and particle diffusion

It is known that systems of charged particles interacting exclusively through electrostatic (Coulombic) forces are inherently unstable (Earnshaw theorem). Yet, in cases of significant screening effects the inverse square law of electrostatic interaction becomes exponential (Yukawa potential). Such systems can, in principle, form stable configurations or configurations whose stability is of a saddle-point kind (stable against some perturbations but unstable against others).

One can consider the formation of quasi-stable configurations in charged dusty plasmas on the basis of the following simplistic model. Consider a linear arrangement of unequal positively and negatively charged dust particles and an electron, for example (+2Q, -Q, e). For every such system there is a saddle point (Earnshaw quasi-equilibrium), such that the escape rate for the electron depends on the direction of its escape. Rene Thom's Catastrophe Theory (mathematical treatment of continuous action producing a discontinuous result) is one of the useful methods for describing such processes. Similar quasi-stable configurations are formed in particle traps which usually combine electric and magnetic fields (Paul, Penning, etc traps).

4.3 Coulombically bound dusty systems

4.3.1 Rydberg quantum states

Rydberg states refer to exited states of atoms which have a very small binding energy and, as a result, very large (on atomic scale) size. The size (the spread of electronic wave function) of a typical Rydberg state is several hundred atomic sizes. In Rydberg states a single electron can be "shared" between two (or more) positively charged atoms or dust particles (like binary stars sharing the same planet). This way an electron can act as a "glue" binding particles together. Such a quasi-binding, even if it lasts temporarily, can improve ESP collection efficiency. Likewise, due to polarizability effects, even neutral (uncharged) dust particles can be involved in connected Rydberg-like systems. The latter could be especially attractive option for the dust and microparticles collection in cases where the overall level of particle charging is low and numerous particles remain uncharged.

4.3.2 Anderson localization in aerosol and dusty plasmas

In case of dispersed systems, like suspended aerosols or dusty plasmas, the way to transcend reductionistic limitations in their description is to consider them as whole (wholistically connected) systems. There are numerous methods developed in theoretical physics for the description of connected (collective) systems. The phenomenon of Anderson localization which was experimentally observed in many disordered system may be of a special relevance for the dusty systems. The essence of it is quantum localization (quantum locking) of a particle in the presence of randomly fluctuating (in space) potential. Thus, systems with Anderson localization have enhanced stability against spatial disintegration. For the case of ESP this could lead to the improved collection efficiency, especially for submicron particulate.

4.3.3 Delta potential method

Specific computational model which can be especially convenient for systems where electrons are shared by multiple centers of attraction is delta well potential model first suggested in 1930-s by Enrico Fermi. This model can accommodate the effects of charge migration in quasi-clusters (quasi-complexes) in ESP charged dusts. Quasi-clusters of Coulombically bound particulate systems (dust particles) in ESP may call for the use of Born-Oppenheimer (adiabatic) approximation which allows a convenient separation of motion of slow moving dust particles and relatively fast electrons, the latter acting as connecting "glue". In terms of electronic transitions large dust particles move adiabatically slow. As a result, a small number of electrons (or even a single loosely bound electron) can bind a significant number of dust particles; this is a kind of binding with allows for the "common dragging" effect such that even neutral particles can be dragged electrostatically.

Thus, a major research challenge here is to find out whether a quantum binding assists ESP collection of a large number of neutral dust particles. If so, we will discover a situation in which electrostatic forces which are acting only on charged particles, can (through the quantum connectivity) help to drag neutral particles along with the charged ones. Additional consideration of magnetism (e.g. by induced magnetic moment on charged particulate and/or by Lorentz force acting on a moving charge) may add additional flexibility in designing optimal particulate trajectories towards collecting electrodes.

4.3.4 Field ionization models

In most cases charging of particulate in ESP systems is facilitated through plasma discharge (e.g., corona discharge) which produces high concentration of electrons and ions which, in turn, subsequently attach themselves to dust particulate. Direct ionization by strong electric field (autoionization or cold ionization) is another option. It provides free electrons by the mechanism of quantum tunneling from metal electrodes. An alternative would be a thermal emission of electrons, however such an
option requires the use of hot cathodes which complicates the ESP process.

A yet another charging channel can be provided by the Auger effect. In this case it means particulate charging through the ionization induced by the energy transfer from the nearby excited molecules; the latter can be produced by corona discharge, laser illumination or injection of excited (metastable) molecules.

4.3.5 Single-electron microelectronics analogies

While the term "single-electron electronics" may sound somewhat odd and redundant, it gains acceptance in physics and electronics community because it refers to the area of active growth and idea generation. Some of these novel ideas can likely be transported to quantum aspects of ESP and dusty systems. This route may be especially promising for nanoscale particulate when the net particle charge is just one or several elementary charges. Furthermore, it is possible that for very small particles (about 10 nm) the differences in their quantum statistical behavior (Fermi-Dirac or Bose-Einstein statistics) could lead to variations in collection dynamics.

4.3.6 Casimir effect and MEMS analogy

Casimir effect in quantum electrodynamics refers to attractive forces due to zero-point vibrations of electromagnetic field. Recently it was applied for the operation of some Micro Electro Mechanical Systems (MEMS). Likewise, Casimir effect can be tested for ESP problems, especially due to the fact that it can create attraction between neutral (uncharged) particles.

5 Spontaneous reduction of wave functions

The "traditional" quantum mechanics is based on the Schrödinger equation which describes the evolution of quantum systems in the same fashion of continuous dynamics as the Newtonian equations of motion describe the behavior of mechanical systems. However, quantum physics runs into some conceptual difficulties in attempting to address the problem of the stability of small particles (R. Penrose).

5.1 Extended and localized wave functions

The essence of the problem is that the Heisenberg Uncertainty Principle maintains that any particle (electron, atom, molecule, or a even a polyatomic object consisting of billions of atoms such as, for example, nanoscale dust particle) which is spatially localized should experience a spread (smearing) of its momentum (velocity). This smearing should result in a gradual delocalization of the particle. Instead of well localized compact object the particle becomes a cloud-like formation whose "size" is constantly increasing.

5.2 Schrödingerian dynamics and quantum collapse

However, in spite of Heisenbergian quantum delocalization, our experience shoes that particles are pretty stable and compact formations. What then offsets the smearing effect prescribed by the Uncertainty Principle? One hypothesis is that in addition to the Schrödinger (continuum) evolution of quantum states there exists another independent process (or effect) which regularly "kicks" any particle in a random fashion and forces it back into a localized state (self-compactification of the quantum state) .

While several specific "mechanisms" of such quantum reductions were suggested, the most plausible (and most esthetically appealing to the author of this paper) is the gravitational reduction of the wave functions (R. Penrose). The key problem to be studied here is the relationship of the efficiency of gravitational quantum reductions to the size of the dust particulate. Some recent theories indicate that the rate of quantum reductions is proportional to the number of elementary particles in a given microparticle. However, it remains somewhat unclear what counts for an "elementary particle" in this case: an electron, every proton and neutron, an entire nucleus, a whole atom? Another aspect is the relationship between gravitationally induced quantum reductions and quantum entanglement in dust particle systems.

5.3 Induced localization and particulate precipitation

On the quantum informational side of the spontaneous localization effects in dispersed dusty systems one can probe links to the recent theories of quantum teleportation of microscopic and mesoscopic objects and spontaneous information generation out of inherent infinite "library of patterns". The latter is exemplified by such computer generated patterns as Mandelbrot set with its infinite complexity and un-repeatability. Using a classic literature metaphor we can recall here a satire by Jonathan Swift (1667 - 1745) who in his "Gulliver's

Travels" describes an "idea generation machine" which the scientists of a flying island Laputa use to generate scientific ideas by random combination of various terms. In spite of a somewhat odd nature of such an idea, its modern implementation in numerous types of random number generators and, most recently, in quantum computing (D. Deutsch, S. Lloyd), may lead to more practical lines of applications, such as formation of specifically "designed" (by natural processes) charge distributions in dusty systems favoring collective drift of a particulate in electric fields towards collecting electrodes.

6 Entropy, ergodicity and informational connectivity

6.1 Informational connectivity in dispersed systems

According to recent ideas on quantum computing, "all physical systems register and process information" (S. Lloyd). This, of course, should not be interpreted as if all physical systems are "alive" in a literal sense - this would be a position of an extreme philosophical panpsychism. And yet the tradition of analogies between unanimated natural systems and systems capable of quasi-biological information processing is common in physics. Starting from the idea of “Maxwell’s Demon” in statistical physics, it presently ranges to such diverse areas as information processing in spin neural networks or ideas about sub-atomic (or even gravitational) foundations of consciousness (J. C. Eccles, H. P. Stapp, B. D. Josephson, R. Penrose, R. Sheldrake). Thus, a quasi-informational response in a system of dispersed dust particles [3] may be akin to targeted mutations in biological systems.

6.2 Macroscopic quantum states and ergodicity

Prime concept of statistical physics is a quantum state. A system of an arbitrary number of particles has a discrete set of quantum states. Although the number of such states is huge (or the order of 10 in power 10^N, where N is the number of particles in the system), this number is still finite. Likewise, the density of states of such systems as a function of total energy is also enormously high, but finite.

The finite (rather than infinite) number of states is a consequence of a quantum nature of the system - in classical physics when the dynamic variables are continuous (rather than discrete) the number of "states" in infinite (actually, has a measure of continuum, using the terminology of the theory of Infinite Sets (G. Cantor).

The term "ergodicity" in statistical physics refers to the fact (or rather to the physical situation) when each quantum state has the same probability of occurrence. If a system is "ergodic" then each and every state of the system will be eventually reached because each state has a finite non-zero (albeit very small) probability of occurrence. Thus, the accessibility of any particular state of the system can be "eased" in quantum coherent systems in which the states are discretely countable rather than uncountable.

For the dispersed dusty systems quantum ergodicity translates into a possibility of reaching any particular quantum state in a finite number of steps, for example such state in which the entire system moves (diffuses) in a coherent way towards the desired location (collecting electrode in ESP case).

6.3 Shannon entropy and informational connectivity

The definition of ergodicity is closely related to the notion of entropy. Actually, the entropy is a much more broadly known concept that the ergodicity - while the entropy is almost always introduced even in the introductory undergraduate physics courses, the ergodicity often is not even mentioned in the graduate level textbooks on thermodynamics and statistical physics. However, for the purpose of our treatment the most important version of entropy is not its traditional thermodynamical definition but its reincarnation in the theory of information known as Shannon entropy.

Shannon entropy is a measure of the informational content of a message. An alphabet where all letters have equal probability of appearance ("informational ergodicity") has the highest information density (and highest Shannon entropy). At a microscopic level the optimization of ESP efficiency is ultimately related to a properly constructed ("designed") charge distributions in dust particulate. This, in essence, means the ability to pinpoint some specific microstate(s) with a particular ("specifically designed") charge distribution. Ability to pick up a given state (or a state from the a narrow subset of microstates) may require some kind of a resonance selection in which the phase point of the system moves over the trajectory in the phase space (ergodic trajectory). All points of such trajectory have the same energy, but differ in their Shannon entropy. The optimization process can likely be physically automated (D.Z. Albert). Although the details of that yet to be developed, here we point to possible analogies with quantum computing algorithms where the optimization of the process proceeds through the reduction of a complex quantum superposition of microstates.

6.4 Order, disorder and chaos in aerosol and dusty systems

Transitions between ordered and disordered states in dispersed system such as dusty plasmas where discussed earlier [3]. Further analogy can be provided by electrostatic structural phase transitions. Matters of specific interest here are the symmetry of configurations of electrical charges on the surface of the dust particles. Depending on the conductivity of the particulate matter, different theoretical treatments can be developed for highly conducting (metal), poorly conducting (insulators) or intermediate (semiconductors) particulate matter.

Such issues as chaos (chaotic dynamics) and self-organized criticality (trend for a system to reach a quasi-stable state at the very threshold of structural stability) are another typical features of loosely bound systems with many degrees of freedom.

6.5 Bose condensation and precipitation enhancement

Along with such collective phenomena as superconductivity, superfluidity and quantum Hall effect, Bose condensation in quantum systems is a manifestation of quantum (non-local) connectedness in spatially extended systems. Although (so far) Bose condensation was observed only in some specific systems at very low temperatures, it may eventually follow the historical path of the superconductivity. The latter has recently "evolved" from the low temperature effect (first discovered in 1911) to the so-called High Temperature Superconductivity (HTC), discovered around 1985. If the on-set of Bose Condensation in dispersed plasma-like dusty systems can be induced at room temperature (perhaps through an action of a coherent resonance radiation, like in laser systems), such a collective (interconnected) system can exhibit a far greater ESP collection efficiency.

7 Conclusion

In indicating a range of possible developments, the author realizes that not all of them are likely turn out to be actually tested and applied to air cleaning systems. And yet, the list of various options presented in this article shows that there is a wealth of unexplored possibilities available on a quantum side of things.

An apparent upfront impossibility of some of the discussed options (especially on quantum information side) may well be trespassed by carefully designed targeted experiments. As history of physics demonstrates, many proclaimed “impossibilities” were later turned to practical realities. Thus, while the ESP air cleaning as such is an applied technological problem of great practical importance, its "marriage" with such a profoundly fundamental area of science as quantum physics may open a cornucopia of new experimental avenues and engineering innovations.

Furthermore, in the same way as the development of the steam engine (J. Watt) has stimulated the development of theoretical thermodynamics (S. Carnot), the “quantum upgrading” of ESP technology will most likely lead to new theoretical and interdisciplinary advancements.

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