Bipolar Ionization: Understanding the Difference Between Theory and Practice

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Executive Summary

Indoor air quality (IAQ) has increasingly become a priority for everyone from homeowners to facility operators. Sifting through the wide range of technologies that claim to improve IAQ can be a daunting task, given the complex chemical mechanisms of action many of these systems utilize.

Yet, a basic understanding of the fundamental process is often critical to understanding whether the theory behind the IAQ improvement claim will translate into the reality of the desired outcome.

This is particularly true for one of the most widely-utilized "air-purifying" methods: air ionization. At its most basic, air ionization technology is a process by which electric currents are used to turn neutral atoms in the air into charged atoms (i.e., ions) that interact with the environment to improve indoor air quality.

While the theory might sound relatively straight-forward, the reality is far more complex. To begin with, there is controversy within the scientific community surrounding exactly how these ions might achieve their effect.[1] And much of the evidence for that effect comes from laboratory-based studies conducted in small chambers which are a far cry from the larger rooms and spaces in which the devices are intended to be used. This is a real concern given that studies have shown not only are these ions short-lived once produced, but also that their concentration and efficacy diminish with increasing distance from the device.[2-3]

There is also evidence that the technologies can generate hazardous by-products such as ozone. Further, even those technologies that have been certified as having "zero ozone omissions" are capable of achieving significant ozone levels based on factors ranging from the surface materials in the room being treated to the age of the device itself.[4-5]

And a key method used by manufacturers to avoid ozone production—lower power/lower electric fields—also means lower ion concentration and, therefore, lower efficacy.[6]

Notably, these potential limitations have led organizations from the Environmental Protection Agency to ASHRAE to issue cautionary statements regarding the technologies.[7-8] Because the goal is to improve IAQ, it is crucial to ensure the "solution" doesn't inadvertently worsen the problem.

What is Air Ionization?

Ionization is the process(es) whereby an otherwise neutral atom is given a positive/negative charge through the removal/addition of an electron, respectively.[2] Electric field air ionization, specifically, describes the process whereby electrons are exchanged between a stream of electric current and molecules within the air (mostly oxygen). In many air ionization technologies, both positive and negative ions are produced (called bipolar ionization), with the end result being a uniform mixture of +/- air ions as well free radicals. This mixture of ionized gas, called a plasma, is created by altering the naturally occurring oxygen and humidity in the air.

Molecules of healthy O_2 gas are altered into negative oxygen ions (O_2^-), called superoxide ions, which are incredibly unstable and highly reactive free radicals. Additionally, air humidity (H_2O) is decomposed into hydrogen cations (H^+) and hydroxyl radicals ($OH\cdot$), the latter also being an incredibly unstable and highly reactive free radical.[2] This mixture of ions is intended to interact with the proximate environment in ways that should, in theory, improve indoor air quality.

Are There Differences Between Air Ionization Technologies?

Bipolar ionization technologies, most notably Corona Discharge and Needlepoint, typically produce the same types of ions, which all have the same theoretical mechanism of action when it comes to combating pathogens, VOCs, and particulates. However, a shared mechanism of action between the various air ionization technologies is not necessarily indicative of a shared method of ion creation.[2] Different companies claim that different air ionization technologies have specific distinctions between their individual methods of ion generation but, nonetheless, they have similar limitations and concerns associated with their use.

Corona Discharge

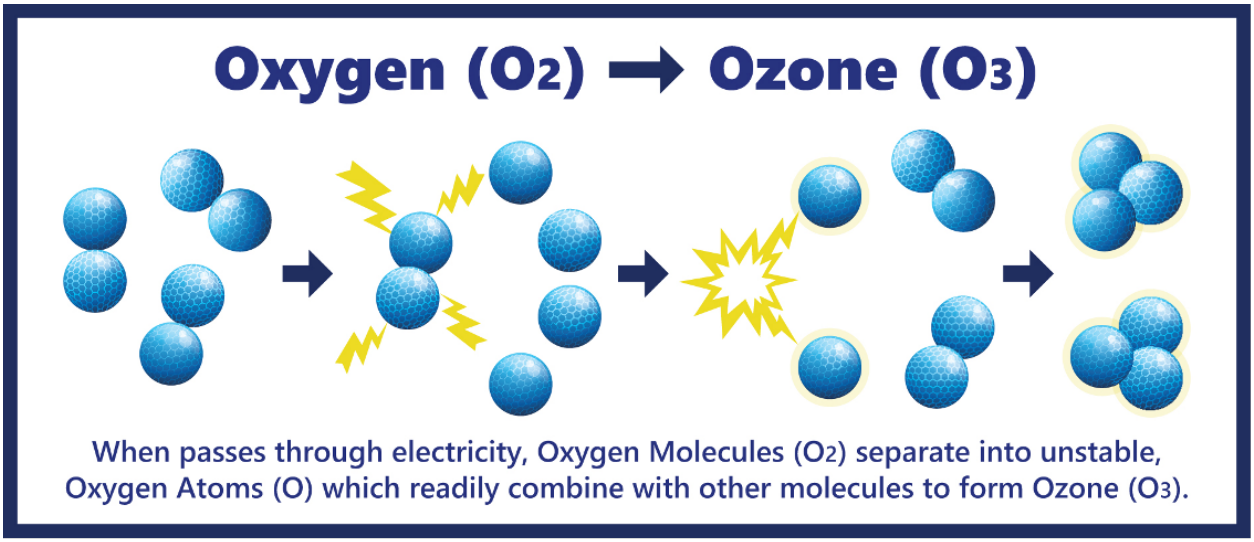
Many air ionization technologies utilize corona discharge to create the aforementioned mixture of ions. Put simply, the technology creates ions using a pair of electrodes or conductors of electrical current. The negatively charged electrode adds electrons to molecules in the air, forming a stream of anions, while the positive electrode takes electrons away from molecules in the air, forming a stream of cations. When these streams are mixed, the result is a uniform mixture of both anions and cations.

The downside to corona discharge ionization, and all air ionization in general, is the potential creation of ozone, which, in addition to its bactericidal properties, possesses oxidizing properties capable of damaging respiratory tissues in humans.[4]

Because this technology utilizes oxygen as a dielectric (i.e., an insulating material that is a poor conductor of electricity), the power of the electric field required by the technology must exceed

the electron volt potential of oxygen (i.e., oxygen gas is directly ionized), resulting in the unwanted recombination of oxygen (O_2) into ozone (O_3).[9]
In other words, the high voltage of corona discharge splits oxygen molecules in the air into two single, unstable oxygen atoms which subsequently combine with other oxygen molecules to form ozone (Figure 1).

Figure 1



Needlepoint Bipolar Ionization

While Needlepoint Bipolar Ionization (NPBI) does, similarly to corona discharge, utilize strong electric fields to produce ions, the manufacturers of the technology adamantly insist that it should not be placed in the same category as other corona discharge ionizers.[10]

The following description of NPBI is based solely on manufacturer claims and is not verified in scientific literature: In contrast to corona discharge technologies, Needlepoint Bipolar Ionization (NPBI) does not directly ionize oxygen. NPBI therefore does not, in theory, result in the production of unwanted byproducts such as ozone, or reduce the production of these byproducts to “safe” levels. In order to directly ionize oxygen, the electric field would need to exceed 12.07eV (the ionization energy of oxygen, measured in electron volts), and NPBI maintains a plasma field of less than 12eV.

Instead, NPBI technologies utilizes a pair of electrodes, one positive and one negative, to create a plasma field (high-voltage electric field) which removes electrons from molecules in the air that possess an electron volt potential less than 12eV. However, in order to be effective at combating pathogens, VOCs, and particulates, it must somehow indirectly result in the creation of both O_2^- and OH· in order to achieve its claimed effect.

The Theory

While there may be certain differences between individual bipolar ionization technologies, most claim to utilize the same general mechanism for fighting pathogens, volatile organic compounds (VOCs), and particulates.

Are There Differences Between Air Ionization Technologies?

While there is currently no consensus on exactly how ions might inactivate pathogens, which are disease causing microorganisms, a common theory involves their exterior surface hydrogens.[1] When OH· molecules bind to hydrogen atoms on the pathogen's outer surface, they can remove the hydrogen atoms from essential exterior structures. The disruption of these exterior structures effectively limits the microbe's reproductive and/or pathogenic functions, and in some cases, leads to its destruction. Pathogens that are not able to bind to hosts are considered non-viable and pose no health threat. However, a number of other theories have also been proposed, making it, as stated by Zhou et al in a study of air ionizers, "…clear that the inactivation mechanism against microorganisms by air ions is still controversial."[1]

Neutralizing VOCs

Volatile organic compounds (VOCs), according to the EPA, are a class of organic gases emitted from thousands of common products and many are capable of inflicting both short- and long-term adverse health effects.[11] Similar to the proposed mechanism utilized for pathogen control, OH· molecules bind to hydrogen from a VOC and result in the breaking of its structural bonds. The result is that the VOC is reduced to harmless compounds, such as oxygen gas (O_2), nitrogen gas (N_2), carbon dioxide (CO_2), and water vapor (H_2O). In reality, many studies have demonstrated inconsistent removal rates of different VOCs and that incomplete oxidation can occur, resulting in equally hazardous byproducts, such as aldehydes.[5,12] Further, in guidance updated in July 2020, the EPA states that, "While ion generators may remove small particles (e.g., those in tobacco smoke) from the indoor air, they do not remove gases or odors," drawing into question this VOC-removal claim.[7]

Eliminating Particulates

Particulates, which are microscopic particles (usually less than a micron in diameter) suspended in the air, also pose various potential health concerns including an increased risk of cardiac and respiratory disease. Bipolar ions (a mixture of both positive and negative ions) adhere to particulates, causing some to become negatively charged and some to become positively charged; these now-oppositely charged particles attract one another, coalesce, and precipitate from the air or become trapped in filters once the particle cluster has gained sufficient mass.[13] Studies have shown, however, that multiple factors including the type of wall surface in a treated room, the concentration of particulates, the particulate size, and the size of the treated room can significantly impact the particulate removal efficacy of ionizers.[13]

The Reality

While some studies have validated these technologies in controlled, experimental scenarios, there are variables in “real-world” deployment that can have a significant impact on their in-use functionality.[3,13]

At stake is not just efficacy but also safety, and end-users may be unaware that many of these variables, ranging from the surface materials in a treated room, to the cleanliness of a device’s electrodes, to the device’s length of operation, can have a significant impact on outcomes.[3,13]

How Long Can Air Ions Exist in an Effective State?

Aside from the potential of these machines to cause the accumulation of ozone within a space, there are also valid concerns about the overall efficacy of bipolar ions within the same space. While there is peer-reviewed research backing the pathogen-, VOC-, and particulate-fighting capabilities of ions, one study by Fletcher has shown that the bactericidal action attributed to air ions is likely grossly overestimated.[14] Additionally, those aforementioned studies, even if accurate within a laboratory setting, may not accurately represent the efficacy of those ions in a real-world setting or within a larger space; the studies that aim to prove these technology’s efficacies are typically conducted in a small chamber/space or in extremely close proximity to the ion generator, which is obviously non-representative of the size of the actual space where they are intended to operate, such as an occupied full-sized room.[3]

In reality, since bipolar ion generators produce both positive and negative ions, and oppositely charged particles are extremely attracted to one another, it is reasonable to assume that those ions would attract and neutralize each other as they move away from the generator or point of production. For example, hydroxyl radicals ($OH\cdot$) readily react with hydrogen ions (H^+) to form water, which is the reverse reaction from when these ions were originally generated. This short lived lifespan of air ions, which is measured in mere milliseconds, is detailed by Daniels.[15] Interestingly, while both corona and needlepoint bipolar ionization theoretically rely on these ions and radicals for their mechanism of action, the American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) cautions that, “Attention must be paid to certain air-cleaning technologies that claim to produce radicals (e.g., hydroperoxy, peroxy, and hydroxyl radicals) that become airborne (gaseous state) as a means of affecting air cleaning/treatment. These species are reactive oxygen species and are well known to be very short-lived in the gas-phase (airborne).

Few studies in the peer-reviewed literature, if any, have measured these radicals in the gas phase as a means of an effective air treatment with such air-cleaning technologies.”[8] This begs the question of how effective these reactive oxygen species can be, given their instability and short lifespan.

Additionally, while there is research demonstrating that particulate removal efficacy is reduced with greater distance from the ion generator,[16] there are minimal published studies that examine the antimicrobial efficacy of ion generators in terms of distance from the technology,[17] and none that examine the antimicrobial efficacy of bipolar ion generators within a larger space. However, one study found that air ion concentration decreased exponentially as distance from the source increased.[18] Further, another study found that the disinfection efficacy of ions is dependent on airflow for distribution and that lower airflow velocity leads to lower disinfection rates,[17] which indicates that these ions are, in fact, rapidly neutralized after the initial generation. Similarly, other research has shown that lower airflow velocity leads to lower particulate deposition rates.[13] Therefore, it can be extrapolated that ion concentration decreases in proportion to the time since generation and, if airflow is kept constant, also in proportion to the distance from the generator.

Put simply, the concentration of ions becomes lower as the distance from the generator increases and,[3,18] since disinfection efficacy depends on the number of ions present, it is fair to assume that antimicrobial properties may also decrease as the distance between the target (microbes) and the generator increases.[17]

Does Ion Concentration Relate to Ozone Emission?

It is a known fact that the ionization of air via electric field has the potential to result in the creation of ozone.[4] One way that many bipolar ionization companies circumnavigate this reality lies in the knowledge that stronger electric fields result in increased ozone emissions and, conversely, weaker fields result in reduced ozone emissions.[6] Thus, in order to minimize the potential of ozone emission, many of these companies must sacrifice the concentration of the ions their technologies produce (lesser electric field strength means less ozone, but also less air ionization and therefore less of the intended air quality improvements).[19] It follows, then, that the consequence of decreased ion concentrations is decreased pathogen-, VOC-, and particulate-fighting capabilities. Indeed, it has been shown that diminished ion concentration causes diminished antimicrobial effects,[1] meaning that these technologies must sacrifice efficacy in order to avoid the creation of ozone. In fact, one study found that when the power was reduced by 50 percent, not only was the ion concentration reduced, but the disinfection efficacy for the two tested bacteria—*Staphylococcus epidermidis* and *Serratia marcescens,* was also reduced by 51 and 34 percent, respectively.[1] Additionally, some of these ionization technologies possess power settings that enable its user to increase the electric field strength beyond recommended levels. Unfortunately, a consumer may not entirely follow the instructions provided by the manufacturer, whether it be by intent or accident, and may increase the power of the ionizer to ozone-producing levels.

How Can Minimal Ozone Emission Ultimately Result in Unsafe Ozone Levels?

The steady-state approximation of ozone describes the concentration of ozone at which the rate of production is equal to the rate of decomposition.[4] In other words, it describes the concentration at which ozone begins to decompose itself and thus maintain a steady concentration throughout a particular space. The steady-state ozone level of a space is proportional to the ozone emission rate and inversely proportional to the rate of ozone removal; so, if even a miniscule amount of ozone is being produced and nothing in the space is reacting with it, it will accumulate until said steady-state concentration is reached.[4]

This fact indicates that even weak ozone generators, including many ionic air purifiers which produce ozone in quantities below the FDA-established safety value (50 ppb[2]) and are able to claim "zero ozone emission" via UL 2998 certification,[20] can ultimately result in steady-state ozone levels that are very much in excess of health standards.

This is especially likely in a closed room with unreactive surfaces such as glass, ceramic tile, or enamel painted walls, since the accumulation of ozone in such a room is additive until the steady-state concentration is reached.[4] It is also likely for rooms with cooler ambient temperatures as they have been associated with higher steady-state concentrations than warmer temperatures.[4] Under these conditions, one study documented an ozone steady state as high as 150 ppb with a certain ionic air cleaner—three times the FDA-established safety limit.[4]

Does the Age of an Ion Generator Affect its Ozone Production?

Many companies that sell needlepoint bipolar ionization technologies boast a UL certification to indicate that their product emits zero ozone. While this may sound reassuring, ozone emissions may not actually be zero once the technology is in use. Namely, aged/dirty electrodes, both for corona and NPBI, are not only known to cause increased ozone production,[21] but also greatly diminish IAQ improvements.[22] When the technology is submitted to UL for testing, it is likely brand new with no wear and tear that would accumulate as the result of prolonged use. As such, the "zero ozone emission" UL test result is likely achieved for a fresher state of the technology that does not entirely represent the technology's state once it is implemented for consumer use. This is important because, as a result of age, the wear and tear inflicted upon the technology from manufacturer-intended use has the potential to induce increased ozone emissions.

It is not entirely unlikely that the same technologies that pass UL testing and become certified as a zero-ozone emission technology would fail the testing if resubmitted after prolonged use.

Similarly, research has shown that for technologies that rely on ozone filters to remove any generated ozone, the effective ozone generation rate increases with the time of operation of the air cleaners owing to the "aging" of the ozone filters.[5]

This issue of prolonged use and change in performance is underscored by ASHRAE in their Position Document on Filtration and Air Cleaning. They state that, "…filtration and air cleaners should be tested for extended durations to examine the possible change of performance in time of operation and the minimum period at which regular performance checks should be made. Information on these aspects is nearly nonexistent, and there are nearly no documents regulating and necessitating examination of long-term performance of filtration and air cleaning devices."[8]

Conclusion

Interest in air cleaning capabilities has grown considerably over recent years and, with it, the number and variety of technologies claiming to achieve this effect.

Ionization technology represents one of the major categories for air cleaners, but concerns over its safety and efficacy have led to cautionary warnings from professional, consumer, and government agencies alike.[7-8,23]

Ozone emission is a widely recognized health risk and, as described here, often subject to a wide range of factors from the device design to use parameters, many of which end-users may not be familiar with. ASHRAE summarizes this risk in their Position Document, “In the absence of robust information regarding safe levels of ozone, the precautionary principle should be used. Any ozone emission (beyond a trivial amount that any electrical device can emit) should be seen as a negative and use of an ozone-emitting air cleaner, even though the ozone is an unintentional by-product of operation, may represent a net negative impact on indoor air quality and thus should be used with caution.”[8] And user beware—some manufacturers may use terms such as "activated oxygen" or "super oxygen" as euphemisms for ozone in an effort to circumnavigate disclosure of ozone emission.[23]

The risk term of the risk-benefit ratio is clear, but the benefit term—effective air “cleaning” and mitigation of allergic symptoms—is less so. ASHRAE states that “studies of ionizers have shown results ranging from no benefit to some benefit for acute health symptoms” and the EPA cautions, “While ion generators may remove small particles (e.g., those in tobacco smoke) from the indoor air, they do not remove gases or odors, and may be relatively ineffective in removing large particles such as pollen and house dust allergens. Although some have suggested that these devices provide a benefit by rectifying a hypothesized ion imbalance, no controlled studies have confirmed this effect.”[7-8] The final calculus, therefore, needs to be a careful one, so that the putative “solution” does not, in effect, worsen the problem.

For more information, get in touch at Synexis.com/Contact.

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