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Adiabatic & Isothermal Humidification for Electronics Manufacturing: The Science of Humidity Control in Manufacturing

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ABSTRACT
Humidification is a key component of an effective ESD program and a process control system (a set of procedures designed to ensure that processes within a manufacturing plant are carried out correctly and that the desired output will be achieved) in an electronics manufacturing facility. Humidification assists in achieving company process control goals by providing another "tool" a company can use to manufacture products that meet company QA/QC standards while reducing costs associated with waste (scrap, rework, etc.) through a robust ESD regime that integrates humidification throughout the program. Secondary effects of providing humidification in electronics manufacturing are increased company ROI and bottom line profitability. This paper provides a closer look at the interconnectedness of adiabatic humidification, improved process control and financial performance.

Key words: Humidification, Humidity, Adiabatic, Isothermal, ESD, ROI.

INTRODUCTION
ESD programs primarily focus on ensuring people have access to and are using the correct ESD tools. Some of the most common tools are antistatic work benches, grounding cords, antistatic tools, antistatic gloves, ESD rubber matting and antistatic clothing, etc. Checklists and inspections are used to ensure compliance with the facility ESD program. However, these all of these tools have one factor in common… they all involve people using the equipment correctly. As good as an ESD program can be, it is rare to see 100% of the people, using 100% of the ESD tools available correctly, 100% of the time. (If you've seen this, please let me know!) Adding systems that do not require people to use the tools correctly at all times, such as humidification, into a facility, will increase the effectiveness of a facilities' ESD program by eliminating the human factor from a portion of the ESD program.

Key International Standards for humidity in electronics manufacturing, waste attributable to ESD and its impact on ROI, an overlooked component (humidity) of a well-rounded ESD program, and new technology that provides humidity for enhancing ESD protection while lowering facility utility costs are interconnected. Additional discussion will focus on adiabatic cooling and its effect on facility equipment and potential long term energy efficiencies, energy savings, cost savings, and rebates that can lead to improved facility financial performance.

KEY INTERNATIONAL STANDARDS
Humidifying for Electronics Manufacturing

IPC J-STD-001F:
When humidity decreases to a level of 30 % or lower, the manufacturer shall verify that electrostatic discharge control is adequate, and that the range of humidity in the assembly area is sufficient to allow soldering and assembly materials to function correctly in the process.

IEC 61340-5-2.2016:
Introducing humidity control within an ESD protected area is a method for reducing electrostatic fields to a permissible level.

JEDEC JESD625B:
Relative humidity has an impact on the formation of electrostatic charges and can thus support an existing ESD protection program.

ESD Handbook TR20.20-2008 section 5.3.16 Humidity:
Relative humidity above 30% in ESD protective areas is desirable as long as other adverse conditions are not created as a result of humidity levels.

Electronics are sensitive to extremes of humidity. High humidity can alter the conductivity in the devices, leading to damage and malfunction, and possibly corrosion. Condensation, also, becomes a very real problem at high humidity. Very low humidity, on the other hand, can cause the components of a device to become brittle and lead to possible dimensional changes and stability issues with boards and components. Therefore, electronics are usually designed for operation in normally-experienced humidity ranges, and so will operate correctly in the range of 30% to 50%.

Waste Attributable to ESD
Electrostatic discharge (ESD) costs the electronic industry billions each year. Some major companies report that 25% of all identified electronic part failure is due to ESD while facilities with a properly implemented ESD program can have an "ROI exceeding five to one within six months." [1] Reducing latent defect field failures is what allows companies to report return on investments of 10:1 from their

ESD Control Programs. [2]

According to the ESD Association "despite a great deal of effort during the past decade, ESD still affects production yields, manufacturing costs, product quality, product reliability, and profitability. Industry experts have estimated average product losses due to static to range from 8-33%." [3] Others estimate the actual cost of ESD damage to the electronics industry as running into the billions of dollars annually. The cost of damaged devices themselves ranges from only a few cents for a simple diode to several hundred or thousand dollars for complex hybrids. When associated costs of repair and rework, shipping, labor, and overhead are included, clearly the opportunities exist for significant improvements.

Static Losses Reported			
Description	Min. loss	Max. loss	Est. avg. loss
Component manufacturers	4%	97%	16–22%
Subcontractors	3%	70%	9–15%
Contractors	2%	35%	8–14%
User	5%	70%	27–33%

Table I. Informal summary of static losses by level.

Figure 1. Static Losses Reported

Considering the astronomical quantities of integrated circuits (ICs) manufactured each year, the mere fact that 3 to 30% of them die in infancy because of ESD represents an impressive amount of money. [4] Even with severe protection measures, some manufacturers still confess that ESD is causing 39% to 48% of their IC rejects. [5]

With loses in the billions of dollars each year from ESD issues due to the high percentage of ESD damaged boards, components, ICs, etc., companies can minimize ESD occurrences leading to fewer damaged components, less waste and less capital expended replacing these items thus improving ROI and bottom line profitability is this area of the business.

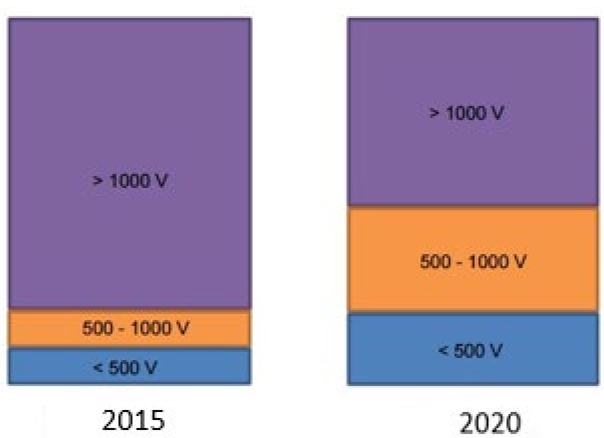

Figure 2. Comparison of Sensitivity Distribution Groups

Humidity as part of a well-rounded ESD program

When reviewing company ESD plans you may notice some of the following focus areas.

- Research and Consult with Experts
- Identify Sensitive Work Areas
- Identify the Sources of ESD within Work Areas
- Establish the Level of Protection Required for Each Work Area
- Develop a Plan
- Institute Static Protection Solutions
- Build Teams and Educate Staff
- Maintain the ESD Control System…

Where does humidification fit into this program? That will depend on the person responsible for the program and the company being willing to implement humidification into the overall program.

Humidity is a natural conductor, which subsequently aids in dissipating electrostatic charges. This reduction in the likelihood of an ESD occurrence along with maintaining optimal humidity levels minimizes brittle material, improves solder quality, enhances productivity, and supports timely delivery. [6]

Looking closer at the ESD Associations thoughts/ideas on humidification as part of an overall ESD program, there was little to be found. All six-parts of the ESD Association series on Electrostatic Discharge (ESD) mention humidity four times, with just one of those mentioning the effect of humidity on ESD.

Many people will notice a difference in the ability to generate static electricity when the air gets dryer (relative humidity (RH) decreases). RH directly affects the ability of a surface to store an electrostatic charge. With a humidity level of 40% RH, surface resistance is lowered on floors, carpets, table mats and other areas… the moisture in the air forms a thin protective "film" on surfaces that serves as a natural conductor to dissipate electric charges. When humidity drops below 40% RH, this protection is significantly minimized, and normal employee activities lead to objects being charged with static electricity.

While 30% - 70% is a suggested range for humidity in an electronics manufacturing facility, ESD literature recommends relative humidity of 40% - 60%. This avoids manufacturing activities in ranges that are borderline low thus increasing the chances of an ESD occurrence or borderline high potentially causing problems with humidity sensitive devices.

Means of static generation	*RH 10-20%*	*RH 65-90%*
Walking across a carpet	35,000 V	1,500 V
Walking on a vinyl tile floor	12,000 V	250 V
Vinyl envelopes for work instructions	7,000 V	600 V
Worker at bench	6,000 V	100 V

Figure 3. Static Generation Activities Comparison

Device type	ESD susceptibility
CMOS	250 - 3000 Volt
OP-AMP	190 - 2500 Volt
VMOS	30 - 1800 Volt
MOSFET	100 - 200 Volt

Figure 4. Device ESD Susceptibility

Adiabatic Humidification Technology

While many people are familiar with Isothermal (Steam) humidification (an air humidification process without changes in temperature), adiabatic technology, while not new, has recently gained interest and in some facilities has replaced Isothermal humidification.

Adiabatic humidification (air humidification by spontaneous evaporation of water without adding energy from the outside) atomizes water into small droplets (1µm - 40µm) which is then introduced into the air via different atomizing technologies (e.g., pressurization, vibration, air/water mix, etc.). For example, 1lbs of atomizes has a surface are of 6,500 ft^2. The adiabatic process does not involve the contribution of thermal energy from an external source. While there is no heat added, there is a cooling effect since the atomized water pulls process heat out of the environment. Typical types of adiabatic humidifiers are high pressure atomizing, compressed air atomizing, and ultrasonic atomizing.

Figure 5. Adiabatic Humidification

Pressure adiabatic technologies utilize medium pressure (300 – 400psi) and high pressure (1,000 psi) pumps that push the pressurized water through supply lines to distribution nozzles with a very small orifice (0.10mm - 0.23mm) which then atomizes the water at the nozzle just before entering the environment in 10µm - 20µm (high pressure) and 40µm (medium pressure) droplets. Compressed air technology utilizes an air compressor to pressurize the water. Then the water/air mix atomizes and enters the environment in 5µm - 10µm size droplets as it exits the nozzle. Ultrasonic humidifiers feature a small water storage tank and piezoelectric transducers installed at the bottom of the tank. The surface of the transducer vibrates at very high speed (1.65 million times/sec), a speed that does not allow the water to move due to its inertial mass. During the negative amplitude of the transducer cycle, a sudden void is created that brings about the production of microscopic bubbles, which are pushed to the surface of the water during the positive amplitude of the cycle. This effect is called cavitation. During this process, the resulting intersecting sound waves created directly underneath the surface of the water cause very small droplets of water to separate, forming a fine mist of vapor that is immediately absorbed by the flow of air.

Most people familiar with humidification technologies will know about Isothermal (Steam) humidification. This process boils water to create steam which is then delivered into the environment through various distribution systems. In simple terms, this process is equivalent to the tea kettle in your house boiling water which creates steam being pushed through the "whistle" on the tea pot to let you know that the water is now ready for use to make your tea.

Figure 6. Isothermal Humidification

Creating humidity with steam uses 333W/lbs of humidity (Please note, humidification requirements (loads) are stated in lbs/hr.). This level of electrical demand is required because the humidifier must constantly keep the water at or very near 212^0 F (100^0 C) so when there is a "call for demand" (need for humidification) the system provides the steam immediately. There cannot be a long delay while the humidifier boils the water from supply temperature typically 55^0F (13^0C) to 212^0F (100^0C) when the humidification is required now. High pressure adiabatic technology uses 1.8W/lbs of humidity. This level of electrical demand is primarily due to adiabatic humidification using supply temperature water instead of boiling water to create steam to provide humidification into the facility. In addition, an inverter is used to modulate the pump speed on pressurized systems, meaning both more precise control of the pump and even lower power consumption.

To help understand the potential cost saving of adiabatic versus isothermal humidification, we'll look at an energy cost analysis study completed in 2022 by the Good Habets Engineering firm which focuses on Sustainable and Renewable Energy. The primary engineer on this study is a P.E. with LEED AP, BD+C, and CEA (Certified Energy Auditor) certifications.

This analysis considers the heating, cooling, economizing, and water use effects of different technologies of humidification. It is run through an 8760-hour simulation using ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) provided weather data. Temperature and Humidity set points, setbacks and heat gains/losses are considered for each hour.

This study focused on providing a few thousand lbs/hr of humidification to a healthcare facility using three different humidification technologies: Isothermal (electricity), Isothermal (gas), and pressurized adiabatic. This study compared utility use, costs, and savings between these three humidification technologies. The specific costs reviewed included water, sewer, electric use, gas use (either directly by the humidifier or for extra heating as required), electric demand (if applicable), and any cooling savings from adiabatic cooling.

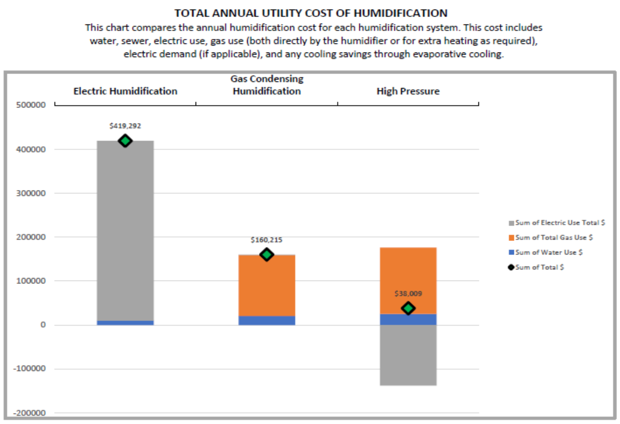

Figure 7. Total Annual Utility Cost of Humidification

The total operating costs per annum for each technology is as follows

- Isothermal (Electricity): $419,292
- Isothermal (Gas): $160,215
- Adiabatic (High Pressure): $38,009

According to the US Energy Information Administration (EIA), the average industrial cost per kW across the US is $0.0845/hr with the lowest rate of $0.0542 and the highest rate of $0.4120/hr. [7]

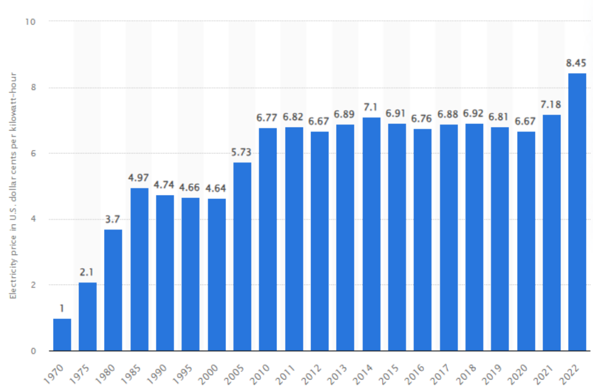

Figure 8. Industrial retail US electricity price 1970-2022

Another faucet of cost savings that was analyzed in the Good Habets Cost Analysis study is the total annual water and total energy use. (Please note that the below chart analyses the cost in MWh instead of kWh.)

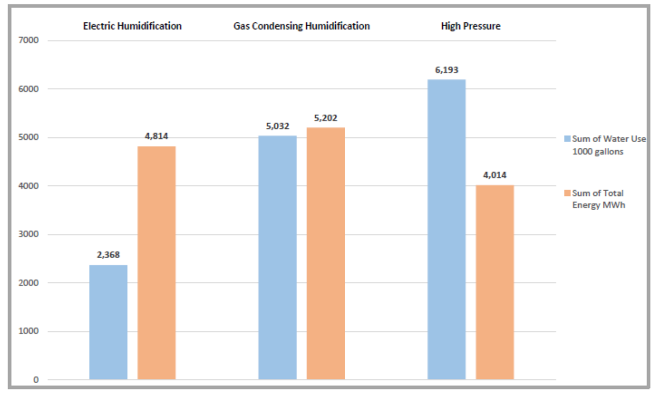

Figure 9. Annual Water and Total Energy Use

The usage difference (in MWh) between the Electric Humidification system and the High Pressure system is 800 MWh or 800,000 kWh meaning the facility will use 800,000 kWh more to power the Electric Humidifier. Looking at the water usage difference between the Electric and High Pressure system, one will notice that the High Pressure system uses 3.8 M gals more water. However, the cost for providing 3.8M gals of water v the cost of 800,000 kWh, is much lower as shown in Figure 9 above.

Secondary Effects of Adiabatic Humidification

While adiabatic technologies provide the humidification needed in the facility it also pulls process heat from the environment. (8,918 BTUs are pulled out of the air using one (1) gal of atomized water). Certain adiabatic technologies use 4W/gal/h (0.004kW/gal/h) of power or .4kW/h per 100gal/h versus 261kWh using an electric commercial AC unit to remove the same amount of heat in the facility.

The difference in electricity usage is driven by adiabatic humidification using a small pump while commercial AC units require much more power to operate. Additionally, adiabatic technology is a “call for demand” based system. Therefore when there is not a need (or no call for demand) for humidification the system reverts to standby mode further reducing the need for electricity. Please note that the cooling achieved through the adiabatic humidification is not comfort cooling but will lower the temperature in most facilities.

Energy savings

The only energy some adiabatic humidification systems consume is used to power the water pump and a small amount of energy used to power the controller which equates to just 4 watts for every gallon/h of capacity. Power consumption is thus minimized. In addition, an inverter is used to modulate pump speed, meaning both more precise control and even lower power consumption. [8] Cooling in summer or in a high heat load facility is provided by lowering air enthalpy (the heat content of a system) through atomized water being pulled from the environment.

While adiabatic cooling is not comfort cooling, it can reduce the temperature in a facility 10^{0}F+ (cooling effect does vary from facility to facility). Dropping the space temperature 1^{0}F requires 3.52kW using a 1 Ton commercial HVAC system while an adiabatic system can drop the temperature approximately 1^{0}F using 1lbs of water which requires 1.8W (0.0018kW) of power. Please note a 50 Ton commercial HVAC system (Air Handling unit) is common for larger buildings so the energy consumption difference can grow quickly.

Figure 10. Commercial Air Handling Unit

One cost that has to be considered with adiabatic humidification is the water consumption. The industrial water and waste water rates vary across the US but an average cost of $2.50/1,000 gals ($0.0025/gal) for water and $4/1,000 gals ($0.004/gal) for waste water is mid-point of the ranges.

Since humidification requirements (load) is measured in lbs/hr, we need to know that 8.35 lbs of water equals one (1) gallon of water. Humidification loads vary by facility so we'll look at the total water cost for 1,000 lbs/hr of humidification. Converting 1,000 lbs of water to gallons, yields 120 gallons of water. Based on the 1,000 lbs/hr load mention above, the cost for the 120 gal/hr of supply water is $0.30/hr. Waste water works a bit differently in that we need to determine how much water from an adiabatic humidifier goes to drain. Adiabatic humidification systems have an absorption efficiency of 95% - 98% when used inside a commercial HVAC duct of Air Handling Unit (AHU) with air velocities of less than 750 fpm. This means that between 2% - 5% of water is not absorbed in the AHU or duct supplying air to the room/facility and is sent to drain. Assuming 120 gal/hr using the upper range (5%) of water to drain, six gals/hr would go to drain costing $0.024/hr. There is an additional amount of water that goes to drain since adiabatic systems use a gravity fed drain design for water in the supply lines to prevent stagnant water from staying in the supply lines. Using a standard 3/8" diameter water supply pipe that is 300' long, we can calculate that the max amount of water the supply line can hold is 1.7 gal. The cost for this waste water is $0.007. Combining the cost for supply water ($0.30) and the total cost of the waste water ($0.024) gives a total water cost of $0.32/gal or $0.038/lbs.

In some facilities, the AHU is undersized for the amount of cooling needed in the space meaning the desired temperatures in cooling mode are not achievable with just the AHU only. This is where the adiabatic cooling effect of adiabatic humidification can be used to lower the space temperature while providing some or all of the humidification load needed in the facility.

AHU units have several other mechanical systems (e.g., Filters, Preheat Coil, Cooling Coil, Reheat Coil, Fans) inside the equipment. The location of each of these must be considered when determining the ideal location of the adiabatic misting grid in the AHU. In some cases, the internal configuration can lead to a hybrid approach of combing a large adiabatic system upstream in the AHU for most of the humidification load and cooling and a smaller "trim" isothermal humidifier downstream in the AHU to provide the final load needed for the facility. While using the hybrid approach will be more expensive than using just the adiabatic humidifier, it will be less expensive than providing the full load with isothermal humidification.

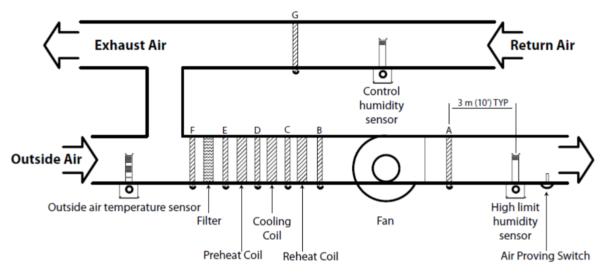

Figure 11. Adiabatic Misting Grid/Manifold Placement in a Commercial AHU/duct system

To show the potential cost savings of adiabatic humidification over isothermal humidification, a 100,000ft^2 electronics manufacturing facility of a global electronics manufacturer in the US Northeast was dealing with very high electricity costs as a result of using isothermal technology. The facility generated so much process heat that even in the winter (Dec, Jan, Feb) they had to run the AHUs in cooling mode to minimize the heat load. The facilities director decided to replace all the isothermal humidifiers with adiabatic humidifiers providing humidity (since humidity was still needed as part of the facility ESD program) but to help minimize the heat load in the space. First full month of operation using the adiabatic humidifiers, the electric bill in the facility was reduced by over $10,000/month. Please note this was not a one-time savings, but a continuous savings month after month. All that savings flowed straight through to the bottom line on the facility P&L without having to produce extra product or cut manufacturing costs in other areas to achieve an increase in net profit. In manufacturing, a piece of capital equipment that has a two (2) year payback period or less (ROI), is highly desirable. In this case the plant manager reported that based on just the energy savings alone, a ROI period of less than one (1) year was expected.

Energy rebates

The current topics in the Commercial/Industrial HVAC and electric companies focus on energy savings, resource conservation, green technology, and most recently, de-carbonization. To help drive companies toward greater use of equipment that meets the requirements of each technology mentioned above, electric and utility companies offer rebates for installing facility equipment that saves kW. After all, an electric company's goal is to pull kW of the grid. Why? Pulling kW off the grid is cheaper than building new power generating stations.

For example, the Puget Sound Energy (PSE) company in Washington State offers rebates as shown below

- $0.45 per kWh saved
- $7 per therm saved
- Up to 70% of eligible project costs (equipment and installation)

Figure 12. Puget Sound Energy Rebates [9]

As a reminder, dropping the space temperature 1^0F requires 3.52kW using a 1 Ton commercial HVAC system while an adiabatic system can drop the temperature approximately 1^0F using 1lbs of water which requires 1.8W (0.0018kW) of power. Comparing the kW usage difference, between the Commercial HVAC system and the adiabatic humidifier, one will find that using the cooling effect of an adiabatic humidifier saves 3.5182 kW (3.52kW – 0.0018kW). Using the PSE rebate of $0.45/kWh, dropping the temperature 1^0F will save the facility $1.58/h (or $15.80/h for a 10^0F). Please note, a common commercial AHU is 50T so the cost savings and rebates grows significantly at larger capacity AHU sizes. This savings (rebate) is based on just the kWh saved so the higher energy consumption levels of large capacity AHU will only increase the rebate based on the $0.45/kWh shown above.

The second savings opportunity is the rebate provided for installing and using energy savings equipment in a facility. As noted PSE will rebate the end user up to 70% of the cost of the project. My experience has been those companies that replace an isothermal humidification system with an adiabatic system, have seen rebates between 25% - 50% of the cost of the project. As an example, if the adiabatic system cost $50,000, the facility could receive a rebate check of $12,500 - $25,000. This rebate would then be applied to the facility P&L thus increasing bottom line profitability while making the final cost of the equipment much easier to fit into the annual budget and a much faster ROI period.

Conclusion

In this paper, the need for including humidification into a well-rounded electronics manufacturing facilities' ESD program, waste and costs attributed to ESD occurrences, adiabatic and isothermal humidification technology, and energy savings and rebates available to a facility for using energy savings technology (adiabatic humidification) are reviewed. Multiple areas that contribute to waste from ESD occurrences and facility energy savings costs and rebates were studied. The most under looked component of humidification, energy savings, and its effect on ROI and company bottom line profitability were presented.

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