Development of a Technique to Measure Deliquescent Relative Humidity of Particulate Contaminants and Determination of the Operating Relative Humidity of a Data Center

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DEVELOPMENT OF A TECHNIQUE TO MEASURE DELIQUESCENT RELATIVE HUMIDITY OF PARTICULATE CONTAMINANTS AND DETERMINATION OF THE OPERATING RELATIVE HUMIDITY OF A DATA CENTER

Jimil M. Shah[1], Roshan Anand, Satyam Saini, Rawhan Cyriac, Dereje Agonafer
Mechanical and Aerospace Engineering Department,
University of Texas at Arlington
Arlington, TX 76019

Prabjit Singh
IBM Corporation
2455 South Road,
Poughkeepsie, NY 12601

Mike Kaler
Mestex, a Division of
Mestek, Inc.,
4830 Transport Drive,
Dallas, TX 75247

ABSTRACT

A remarkable amount of data center energy is consumed in eliminating the heat generated by the IT equipment to maintain and ensure safe operating conditions and optimum performance. The installation of Airside Economizers, while very energy efficient, bears the risk of particulate contamination in data centers, hence, deteriorating the reliability of IT equipment. When RH in data centers exceeds the deliquescent relative humidity (DRH) of salts or accumulated particulate matter, it absorbs moisture, becomes wet and subsequently leads to electrical short circuiting because of degraded surface insulation resistance between the closely spaced features on printed circuit boards. Another concern with this type of failure is the absence of evidence that hinders the process of evaluation and rectification. Therefore, it is imperative to develop a practical test method to determine the DRH value of the accumulated particulate matter found on PCBs (Printed Circuit Boards). This research is a first attempt to develop an experimental technique to measure the DRH of dust particles by logging the leakage current versus RH% (Relative Humidity percentage) for the particulate matter dispensed on an interdigitated comb coupon. To validate this methodology, the DRH of pure salts like $MgCl_2$, NH_4NO_3 and NaCl is determined and their results are then compared with their published values. This methodology was therefore implemented to help lay a modus operandi of establishing the limiting value or an effective relative humidity envelope to be maintained at a real-world data center facility situated in Dallas industrial area for its continuous and reliable operation.

Keywords: airside economization, deliquescent relative humidity, particulate contamination, critical relative humidity

NOMENCLATURE

IT	Information Technology
ASE	Airside Economizer
CRH	Critical relative Humidity
DRH	Deliquescent Relative Humidity
PCB	Printed Circuit Board
GND	Ground
I2C	Inter-Integrated Circuit
RH%	Relative Humidity percentage
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
MERV	Minimum Efficiency Rating Value
RoHS	Restriction on Hazardous Substances
PTFE	Polytetrafluoroethylene
mA	Mili Ampere
V	Volt
IDE	Integrated Development Environment
SIR	Surface Insulation Resistance
RDC	Research Data Center
SDA	Serial Data Line
SCL	Serial Clock Line
VCC	Voltage Common Collector

1. INTRODUCTION

An airside economizer (ASE) is defined by ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) as an arrangement of a duct, a damper and an automatic control system that works in conjunction with the cooling systems, under favorable climatic conditions, to supply outside free cold air, thus, eliminating or reducing the requirement for mechanical cooling [1]. In particular, ASHRAE

[1] Contact author: jimil.shah@mavs.uta.edu

guidelines has an expanded "Recommended" and "Allowable" temperature and humidity zones allowing up to 35-45ºC inlet temperature for short periods of time thus making airside economization extremely useful. This efficient cooling method draws in outside air from the ambient and is then filtered using MERV (Minimum Efficiency Rating Value) 11 or MERV 13 filters to eliminate particulate contaminants before being introduced into the cold aisle of a data center. The amount of enthalpy in the air is acceptable and no auxiliary conditioning is required if the outside air is both sufficiently cool and dry. This mode of cooling operation is generally termed as free cooling [2]. Utilization of ASEs result in significant reduction in energy consumption of a data center in association with the cooling infrastructure. The risk that comes with the use of ASEs is that the temperature and humidity levels must be within specified ranges and more importantly is the entry of particulate and gaseous contaminants that should be within the allowable cleanliness standards.

The physical environment surrounding the IT equipment is mainly defined by temperature, relative humidity and gaseous and particulate contaminants [3-8]. These factors can have adverse effects on IT equipment and can cause its failure in two ways: First type of failure is caused by corrosion of silver termination in surface mount components leading to electrical open circuits. This type of failure mode occurs mainly in geographical areas with high levels of Sulphur bearing gaseous contaminants [9]. Manufacturers have improved their hardware to tackle this failure mode. The second type of failure is caused by a few mechanisms that result in electrical short circuits: (i) In 2006, the European Union's RoHS (Restriction on Hazardous Substances) directive banned the use of lead in solders. This led to changes in the surface finish of Printed Circuit Boards (PCBs) increasing failure rates of PCBs because of creep corrosion [10-12]. (ii) Electrochemical reactions such as ion migration; and cathodic and anodic filamentations [13], and (iii) Particulate matter that settles on PCBs adsorb moisture thereby reducing surface insulation resistance between the closely spaced features on PCBs.

When considering the impact of dust on the reliability of IT equipment, the focus is mainly imparted on the ionic content of dust particles because they have the tendency to dissolve in water and conduct electricity. When dust begins to absorb moisture and when it eventually forms a saturated solution, the major cations and anions are Na^+, NH_4^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO^{3-}, F^- and SO_4^{2-} [14]. Two extremely common consequences of particulate or dust contaminations on printed circuit boards are electrochemical migration and loss of impedance, i.e. the loss of surface insulation resistance, between traces and component leads. These two failure mechanisms involve the contamination by creating a path flow for leakage current.

Relative humidity can significantly influence IT equipment reliability. For example, the deteriorated performance of IT equipment through increased dissipation factor and PCB epoxy dielectric constant. Next, the presence of gaseous contamination leads to enhanced corrosion and a decrease in the surface insulation resistance in the presence of particulate contamination. In simple terms, relative humidity (RH) is defined as the amount of water vapor in the air and is generally expressed as a percentage of the maximum amount of water vapor that the air could hold at the given temperature [15, 16]. Critical Relative Humidity (CRH) is defined as the relative humidity at which the salt or dust particles just begin to absorb enough moisture to start becoming electrically conductive. Deliquescence Relative Humidity (DRH) is defined as the relative humidity at which the salt or dust particles begin the formation of a saturated salt solution. Accumulated particulate matter with low deliquescence relative humidity is of major concern [15, 16].

1.1 Existing DRH Measurement Techniques

It is imperative to develop a practical test method to determine the DRH value of the accumulated particulate matter found on PCBs. With respect to the measurement of the DRH of pure salts, there are two experimental methodologies the Gravimetric and the electrical impedance method.

1.1.1 Gravimetric Method and Its Limitations

This method focuses on measuring the weight of the salt at different values of relative humidity. With a plot of the weight of the salt vs RH%, the DRH of the salt can be determined. This plot can also be termed as a growth curve for salt particles. A micro-gravimetric balance is employed in measuring the weight of the salt. The ideology behind this method comes with the adsorbing nature and hence the increase in the weight of the salt sample. Thus, the value of relative humidity at which there is a sudden change in the weight of the salt is said to be its DRH value.

There are a few limitations related to the Gravimetric method such as the tendency of salts to actively react with the surrounding environment. Before starting the experiment, it is very important to make sure that the environmental chamber is completely devoid of any moisture content. Since this method focuses on the mass change as a function of DRH, it is important to be extremely cautious with the experimental setup. The step range is 2% of relative humidity. Only when the change in mass over time becomes negligible for a certain value of relative humidity, the sample is in a state of equilibrium with the water vapor and only then its mass is recorded. Thus, this method would take a much longer time to give out results and thus determine the corresponding DRH of the salt. Despite all the cautions, the results obtained by this method do not completely match the published values [17, 18].

1.1.2 Electrical Impedance Method and Its Limitations

A conductivity cell that comprises of two platinum electrodes and a piece of porous paper is used for the DRH measurement of the salt sample. The porous paper is wetted with the salt solution to help develop an evenly distributed layer of salt crystals between the platinum electrodes when the relative humidity is lower than the DRH. The paper is placed on a surface that is arched and made of polytetrafluoroethylene (PTFE). At

RH values above the DRH of the salt, the salt absorbs the moisture and forms an aqueous solution. The arched surface allows this excess liquid to drain off and thus maintain a constant thickness of the conducting layer.

Like gravimetric methods, the electrical impedance method also has some limitations. Since this method uses platinum electrodes and data acquisition units, the experimental setup is very expensive and complicated. The process is time-consuming as well since each experimental run is carried out for an interval of 23 hours. The results obtained must further be substantiated with concrete literature to help validate the technique [17, 18].

This study proposes a precise and cost-effective technique to measure DRH of particulate contaminants found in a data center utilizing airside economization. To accomplish this, an experimental technique to measure the DRH of dust particles by logging the leakage current versus RH% for the particulate matter dispensed on an interdigitated comb coupon is used. The methodology is then validated, by comparing the values of DRH of pure salts like $MgCl_2$, NH_4NO_3 and NaCl with their published values. After that, a similar experiment was carried out using the particulate contaminants samples collected from the real-world data center.

2. PROPOSED EXPERIMENTAL METHOD TO DETERMINE THE DRH OF PURE SALTS

2.1 Experimental Setup

To perform this operation, the Thermotron SE-600-10-10 Environmental Chamber was used as shown in Figure 1. The Thermotron incorporates a wide range of applications and specific compressor selections ranging from 3 to 15 HP, a temperature range of -70°C to +180°C and a humidity range of 10% - 98%. The temperature in the experiment is maintained at 25°C and the relative humidity varies from 10%-90% with an increment of 10% RH at regular time intervals of 1 hour and 30 minutes [19, 20].

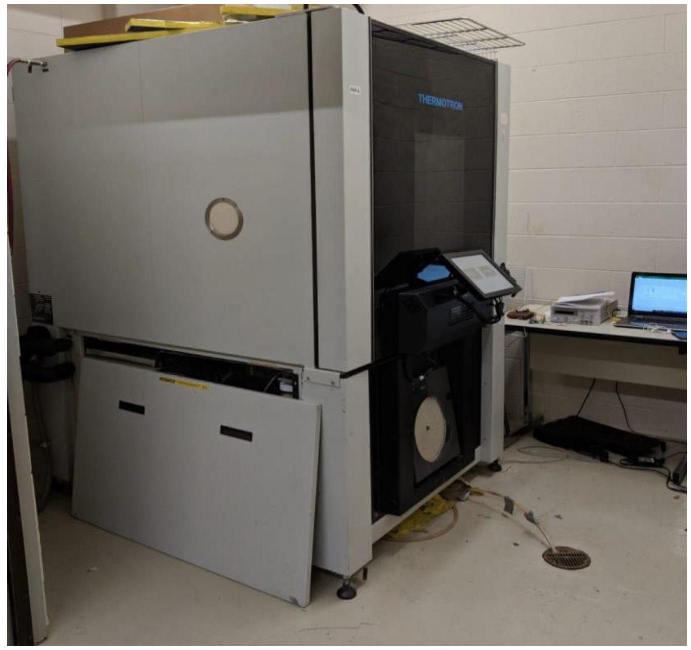

Figure 1: ENVIRONMENTAL CHAMBER: THERMOTRON SE-600-10-10

To specifically evaluate and understand the interactions between solder masks, solder paste and fluxes, the Institute for Printed Circuits, also called the IPC, designed the ‘IPC-B-25A Multipurpose Test Board’ or the ‘PCB-B-25A Test Board’. Another vital function of this test board is to evaluate the effects of moisture on the insulation resistance of solder masks. Figure 2 shows the IPC-B-25A Multipurpose Test Board that is used in this experimental method. The comb coupons E and F were specifically used for this experiment.

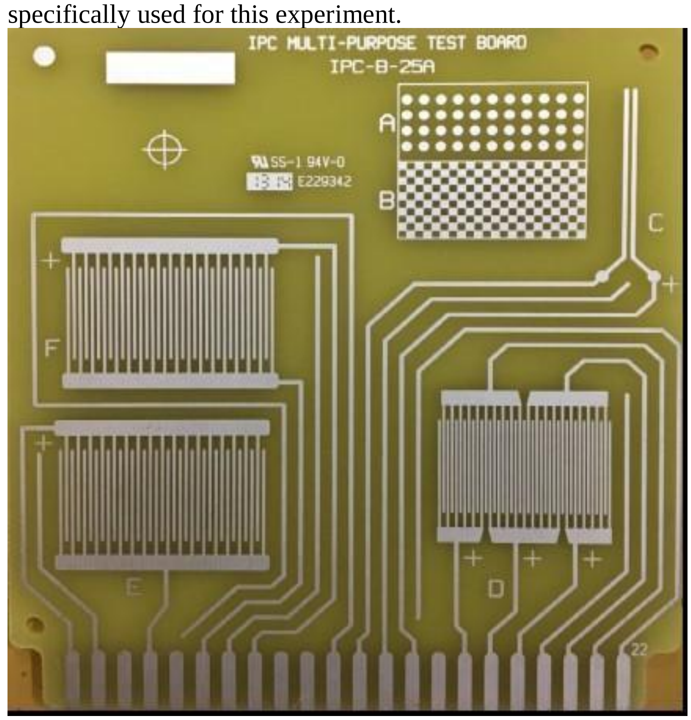

Figure 2: IPC-B-25A MULTIPURPOSE TEST BOARD

This experiment requires a very precise application of 1 V which was provided by the 'Agilent E3614A' power source. The constant voltage (CV) mode is used to provide the desired 1V as shown in Figure 3. It is important to apply very low supply voltage to detect leakage current without causing any electrochemical reaction in the inter-combs, thus, affecting the microbalance of the salt solution [15]. Therefore, a voltage of 1 V is used for this purpose. The Adafruit INA-219 current sensor was used to measure the leakage current. This current sensor was coupled with an Arduino Uno board. A program was developed to help this setup accurately measure and display the value of leakage current at each instant when a voltage is applied across the ends of each comb coupon. The INA-219 sensor helps in obtaining solutions for all power monitoring problems keeping the margin of error of less than 1%. Figure 3 displays the current sensor with the screw terminals.

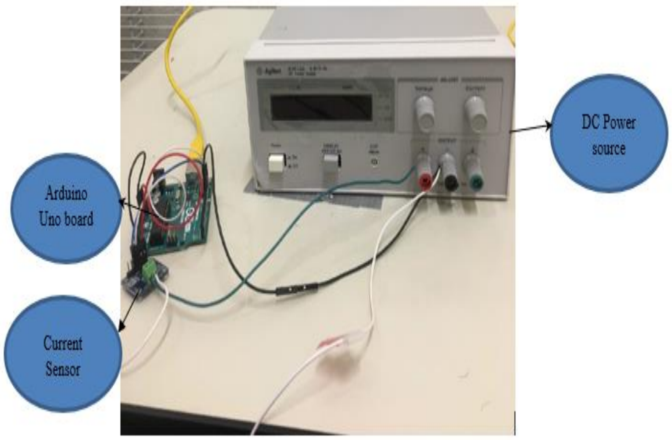

Figure 3: SETUP OF CURRENT SENSOR, ARDUINO UNO AND DC POWER SOURCE

Arduino Uno, as shown in Figure 3, is one of the most commonly used open-source micro-controller board among many available boards in the market. The Arduino Uno board consists of a 16MHz quartz crystal, a power jack, a reset button, 6 analog pins and 14 digital pins that can be interfaced to various other circuits or expansion boards. The Arduino Integrated Development Environment (IDE) is used to program the Arduino Uno via a USB cable. The 5V pin on the Arduino can be used to power up the INA219 current sensor breakout board. The sensor communicates with the Arduino via I2C. Dupont cables are used to make the interconnects between the Arduino and the INA219 current sensor thereby allowing them to freely communicate.

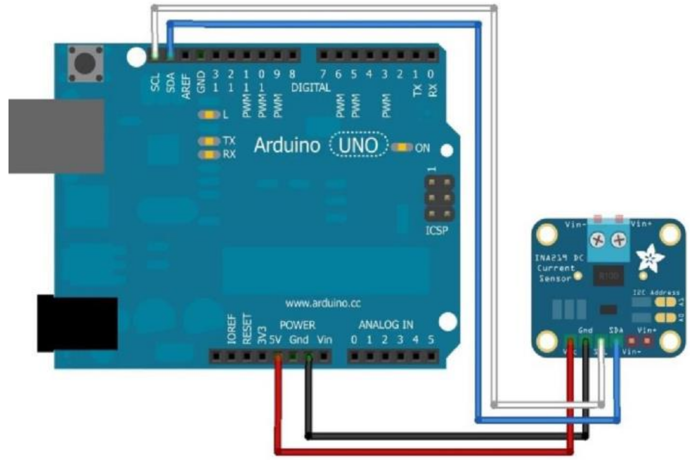

Figure 4: INTERCONNECTIONS BETWEEN THE ARDUINO AND THE INA219 CURRENT SENSOR

Figure 4 shows the coupling of the current sensor to the Arduino. The interconnects made are shown in Figure 4, where the GND, 5V, VCC, SDA and SCL of the Arduino are connected to the GND, 5V, VCC, SDA and SCL of the current sensor respectively. The positive screw terminal of the DC power source is connected to the positive terminal of the sense resistor on the current sensor. The negative terminal on the current sensor is soldered to the positive terminal of the comb coupon (load). Lastly, a connecting wire from the negative terminal of the power supply is connected to the GND on the Arduino and is soldered to the negative terminal of the coupon.

2.2 Experimental Procedure to determine DRH of pure salts

One of the most detrimental materials found in dust is chloride. Chlorides accelerate the electrochemical failure mechanisms such as electrolytic corrosion and metal migration when combined with moisture in the environment and an electrical bias. The presence or existence of ammonium ions can decrease the SIR (Surface Insulation Resistance) of PCBs in the presence of moisture. The existence of Na+ in the surface moisture film can lower the SIR and greatly increase the conductivity of PCBs [15].

Three salt solutions of lab grade Sodium Chloride (NaCl); Ammonium Nitrate (NH_4NO_3); and Magnesium Chloride ($MgCl_2$) are used in this experiment to determine their DRH as shown in Figure 5. 10mg of the salt is dissolved in 10ml of deionized water thus resulting in the 0.1 wt% concentration. The DRH of the salt doesn't vary with its concentration.

Figure 5: SODIUM CHLORIDE; AMMONIUM NITRATE; AND MAGNESIUM CHLORIDE SOLUTIONS RESPECTIVELY

Connecting wires were soldered to the comb coupon interconnections and were cleaned with Isopropyl Alcohol to avoid any effect of the solder flux on the circuitry. After placing the comb coupon in the environmental chamber, 10 drops of the salt solution were carefully dispensed on the coupon using a suction syringe. A pipette can also be used. Figure 6 displays the salt solution dispensed on the comb coupon. One salt sample is tested at a time to ensure the controlled approach.

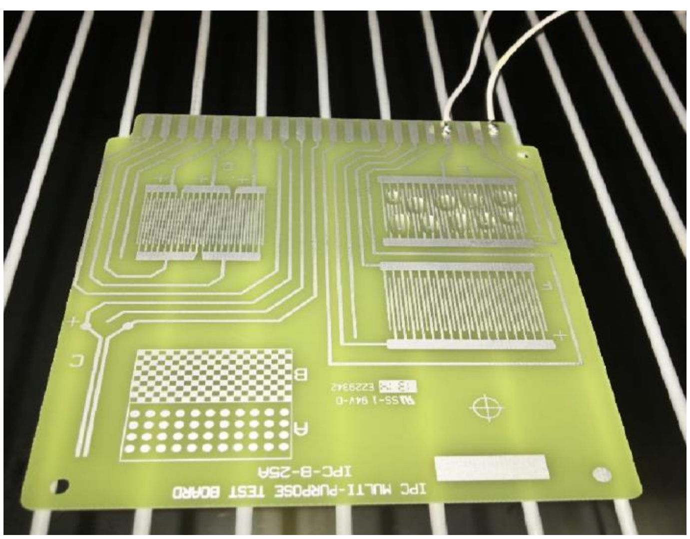

Figure 6: 10 DROPS OF THE SALT SOLUTION CAREFULLY DISPENSED ON THE COMB COUPON.

It is very important to make sure that the comb coupon remains in the environmental chamber during the entire course of the experiment. The salts tend to quickly react or reach equilibrium conditions with the environment that surrounds it. Therefore, it is vital that the coupon remains untouched and undisturbed during the entire course of the experiment to obtain accurate results. The environmental chamber was set to a fixed temperature of 25°C and a relative humidity of 10% and then allowed to rest for a period of 12 hours. This step is performed to allow the saturated salt solution to get rid of its moisture content thereby allowing just the salt particles to settle on the coupon and to achieve an equilibrium with the fixed environment inside the chamber.

After that the DC voltage of +1 V is passed through the comb coupon for 1-2 seconds, immediately after which a voltage of -1 V is applied to counter the effect of +1 V on the circuit to maintain the microbalance of the salt solution. The INA219 current sensor coupled with the Arduino Uno board helps in displaying the load voltage and leakage current. The relative humidity is gradually increased by an increment of 10% for a duration of 90 minutes each. This allows the salt to attain equilibrium with new relative humidity conditions. The load voltage and leakage current are measured again. This process is repeated until a relative humidity of 90% is achieved. The values of RH%, Leakage current (in mA) and Log of leakage current are tabulated. A graph of the log of leakage current is plotted versus the RH%. This plot helps in determining the CRH and DRH of the respective salt that is being tested. The experiment is repeated for the remaining salt samples.

3. TO DETERMINE THE OPERATING RELATIVE HUMIDITY OF A DATA CENTER USING THE PROPOSED EXPERIMENTAL METHOD

The samples of the particulate contaminants were collected from servers located in the Research Modular Data Center in Dallas, Texas [20]. The samples were collected using deionized water and stored carefully in air-tight test tubes. To collect the samples, four servers were removed from the center of the four different racks and the interior of the servers was exposed by removing the top cover. After this, deionized water was poured on the server board and chassis to generate sample solution with contaminants in the form of a slurry as shown in Figure 7. The sample solutions were collected in a test tube and then closed with an air-tight rubber bush for safe storage. A total of five different samples were collected including one sample of the facility water and four samples from different servers as shown in Figure 7. The sample from the facility water is collected to check for its ionic content due to presence of various minerals which might, after evaporation in cooling pads, enter in the data center space along with the cooling airflow.

Figure 7: COLLECTED DUST SAMPLES FROM SERVER CHASSIS

We used the same experimental set up as explained in section 2.1. The connecting wires of the current sensing circuit were soldered to the positive and negative terminals of the multipurpose test board and the solder flux was cleaned using Isopropyl Alcohol. The coupon is then placed in the environmental chamber and 10 drops of slurry from the first server sample were dispensed on the board by a sanitized syringe. The connecting wires from the chamber are routed to the DC power supply and the current sensor. As outlined in the experimental setup, the connections are made, and the chamber door is then shut. A steady temperature of 25°C is maintained throughout the cycle and a rest period of 12 hours at 10% Relative Humidity is allowed. Once the first cycle is complete, a DC voltage of +1 V is applied across the test coupon and the leakage current is monitored using a JAVA script on an Arduino software tool. After taking the reading at +1 V, a voltage of -1 V is passed immediately across the test coupon to counter the effect of +1 V. The RH% is then increased by 10% for the next cycle keeping the ambient temperature of the chamber same as the previous cycle and leakage current is measured in a similar manner. The above three steps are repeated till an RH% of 90% is reached. The obtained values of leakage current are recorded in a table against the RH% values and a graph is plotted between RH% and leakage current. The values of DRH and CRH are obtained from this graph. The experiment was repeated for the remaining samples from the servers and the facility water.

4. RESULTS AND DISCUSSION

4.1 Pure salts samples

Observing the linear plots for all three salt samples, it is rather tempting to interpret the linear plots in terms that the sudden increase in electrical conductivity (or leakage current) being the DRH value of the salts. But the DRH values based on the linear plots do not coincide with their published values. Also, they depend on the magnitude of the vertical scale. To overcome this drawback and to obtain the DRH values as those in published literature, the logarithm of leakage current against RH%, when +1 V is applied, is plotted as seen in Figures 8(a), 8(b) and 8(c) for NaCl, NH_4NO_3 and $MgCl_2$ respectively.

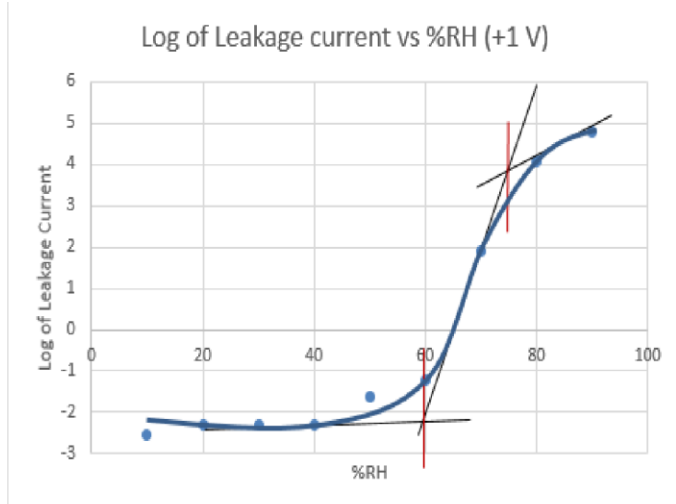

Figure 8(a): LOGARITHMIC PLOT OF LEAKAGE CURRENT VERSUS RH% FOR NaCl

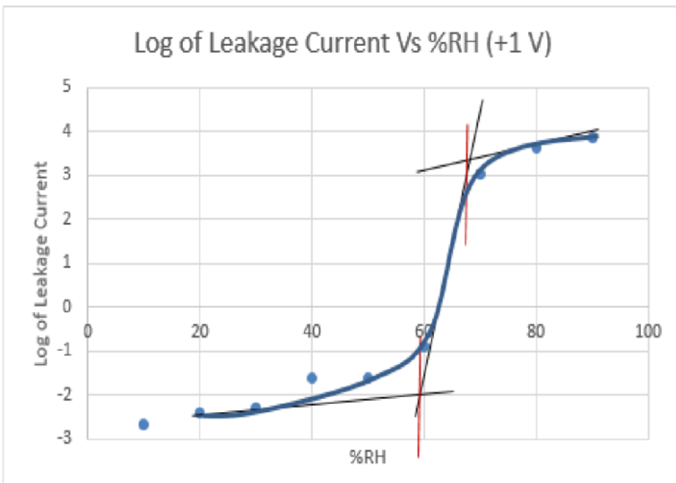

Figure 8(b): LOGARITHMIC PLOT OF LEAKAGE CURRENT VERSUS RH% FOR NH_4NO_3

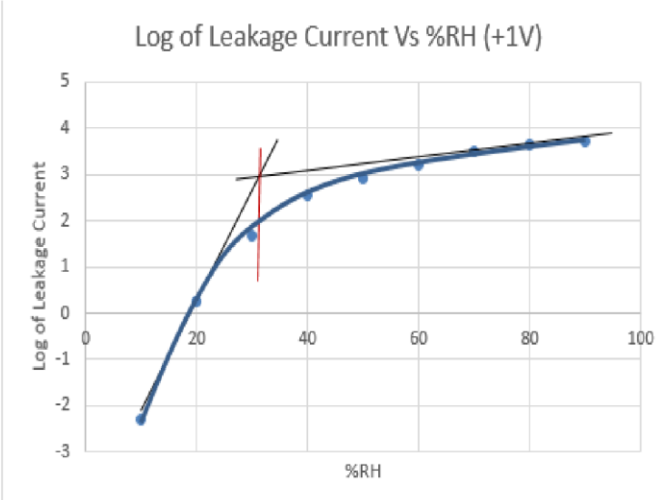

Figure 8(c): LOGARITHMIC PLOT OF LEAKAGE CURRENT VERSUS RH% FOR $MgCl_2$

The curves which are S-shaped can then be made piecewise linear by drawing straight lines to cover the inversion region, the straight lines are the lower relative humidity asymptote and higher relative humidity asymptote. The intersection of the lower relative humidity asymptote and the inversion line corresponds to the CRH of the salt. At this value the leakage current begins to rise sharply with the increase in RH%. The intersection of the inversion line with the higher relative humidity asymptote corresponds to the DRH of the salt.

At lower humidity ranges, the salt is generally in equilibrium with the humidity. Thus, a small increase in the relative humidity does not lead to a considerable change in the electrical conductivity of the salt as the salt stays relatively dry. There is a rapid rise in the conductivity as the salt absorbs enough moisture to start approaching the deliquescence state. This can be noticed by the high slope of the inversion region.

Table 1 shows a comparison of the DRH of salts obtained by the performed experiment, using logarithmic plots, with their published values at 25°C. It is seen that the experimentally obtained results are in a good agreement with the published values thereby validating this experimental approach.

Table 1: COMPARISON OF EXPERIMENTAL VALUES OF THE DRH OF PURE SALTS WITH THEIR PUBLISHED VALUES [19]

Salt	Published Values at 25°C	Experimental Values (Logarithmic Plots)
Sodium Chloride	CRH: 61% DRH: 75.8%	CRH: 61% DRH: 75.5%
Ammonium Nitrate	CRH: 59% DRH: 63%-64%	CRH: 59% DRH: 63%
Magnesium Chloride	DRH: 32.78%	DRH: 32.5%

During the experiment, when the RH% exceeds the DRH of the salt and the voltage is applied across the terminals of the test board, the salt solution begins to corrode the coupon. The before and after pictures of the comb coupon dispensed with NaCl (a), NH_4NO_3 (b), and $MgCl_2$ (c) solutions are as seen in Figure 9 depicts the effect of relative humidity in the presence of particulate contamination. The corrosion effects are also very evident.

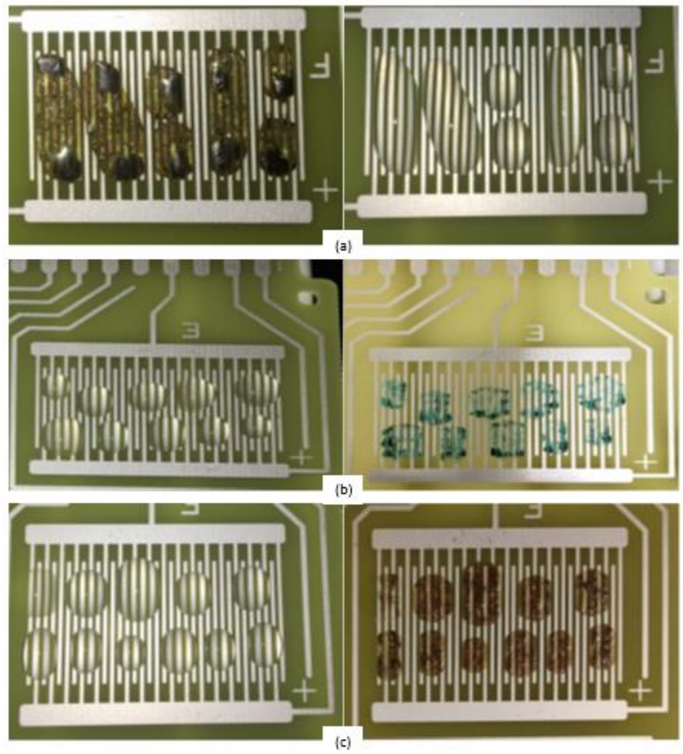

Figure 9: BEFORE AND AFTER IMAGES OF THE COMB COUPON DISPENSED WITH SALT SOLUTION

4.2 Research data center samples

Figures 10(a), 10(b), 10(c), 10(d) and 10(e) display the linear graphs of leakage current versus RH% when +1V has been applied for four servers and facility water samples respectively.

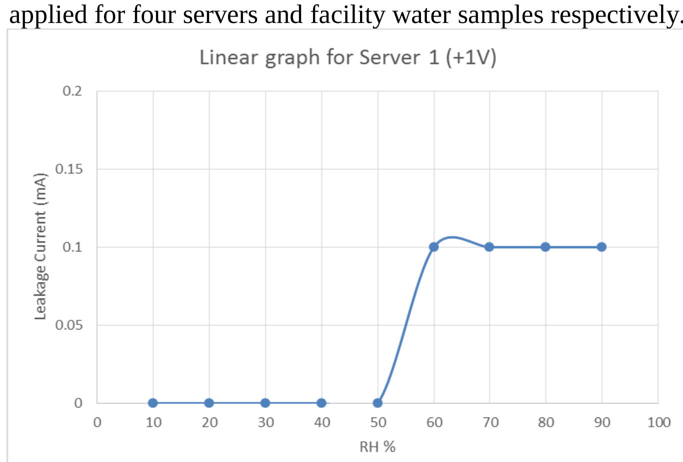

Figure 10(a): LINEAR GRAPH OF LEAKAGE CURRENT VERSUS RH% FOR DUST SAMPLE FROM SERVER 1

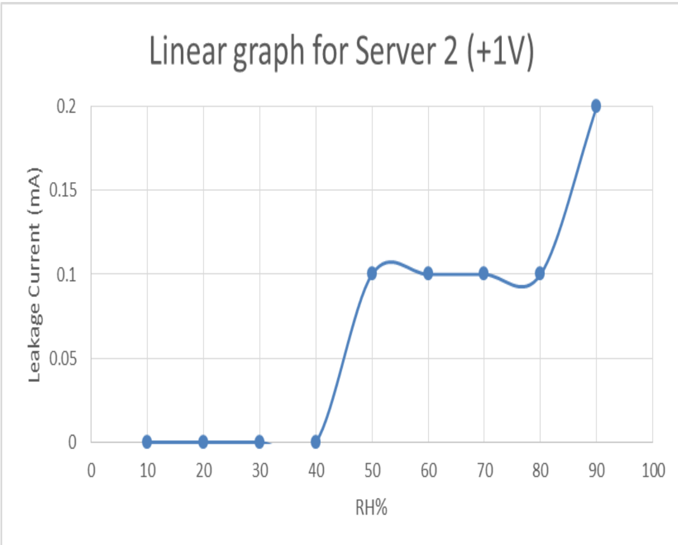

Figure 10(b): LINEAR GRAPH OF LEAKAGE CURRENT VERSUS RH% FOR DUST SAMPLE FROM SERVER 2

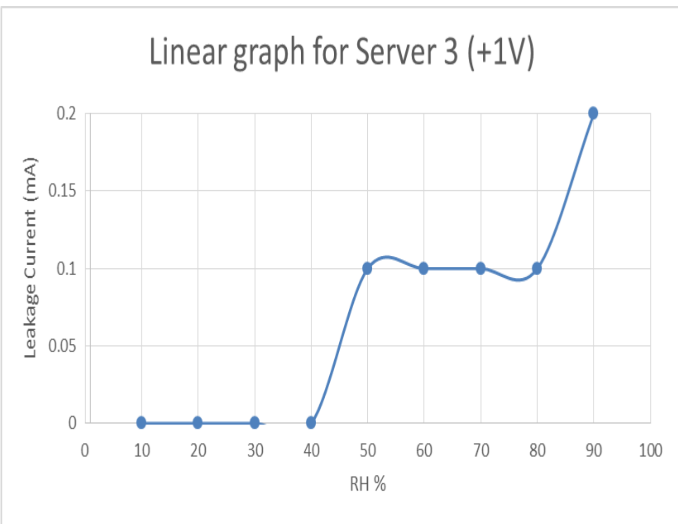

Figure 10(c): LINEAR GRAPH OF LEAKAGE CURRENT VERSUS RH% FOR DUST SAMPLE FROM SERVER 3

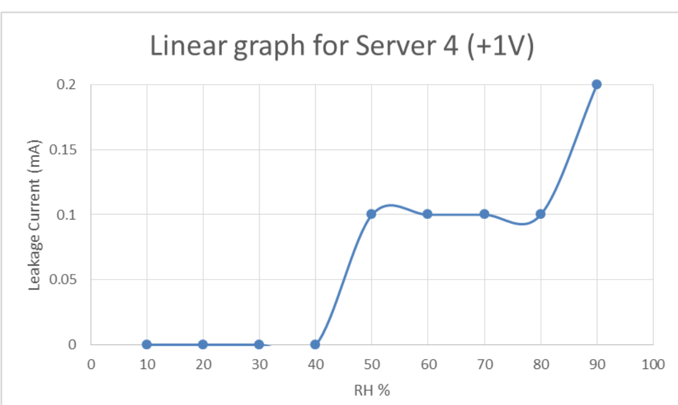

Figure 10(d): LINEAR GRAPH OF LEAKAGE CURRENT VERSUS RH% FOR DUST SAMPLE FROM SERVER 4

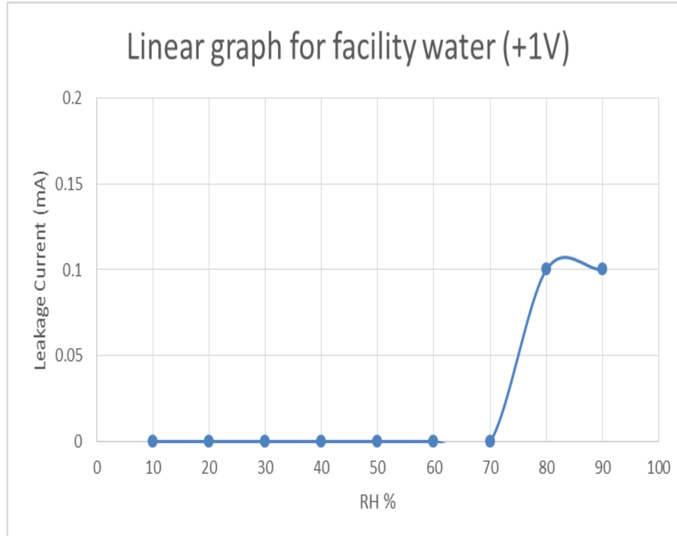

Figure 10(e): LINEAR GRAPH OF LEAKAGE CURRENT VERSUS RH% FOR FACILITY WATER SAMPLE

The above graphs show the values of leakage current obtained from the current sensor against the increasing value of RH% for +1 V. As evident from the linear graphs, we can see a sudden increase in the value of leakage current at RH% of 50%-60% for server samples and 80% for facility water sample respectively. The sudden increase in leakage current attributes to the fact that there is an increase in electrical conductivity at the test board. This happens when the salts present in the contaminated slurry absorb moisture enough to form an aqueous solution and become conductive. To get the exact values of the DRH, the logarithm of the leakage current can be plotted against the RH% values. We used current sensor INA 219 which can only show current values in mA till one decimal place rather than precise values till three decimal places, which are required to generate a smooth logarithmic curve. The before and after pictures of the comb coupon dispensed with the sample collected from the first server are shown in Figure 11.

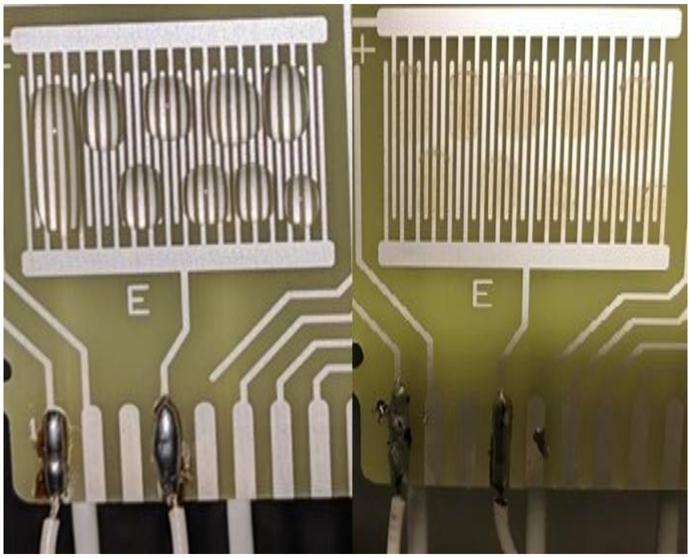

Figure 11: BEFORE AND AFTER IMAGES OF THE COMB COUPON DISPENSED WITH THE FIRST SERVER SAMPLE

5. CONCLUSION

In this study, an effective method to determine the DRH of dust is proposed. The experimental methodology is validated by determining the CRH and DRH of pure salts i.e. NaCl, NH_4NO_3 and $MgCl_2$ and then comparing it with their published values. At higher relative humidity ranges, the SIR between the features on the coupon drastically decreases. Salt or dust has the tendency to absorb moisture, which then becomes wet and starts conducting if the relative humidity in the data center rises above its DRH. The salt begins to conduct electricity and the images obtained after the experiment clearly display the corrosion that takes place. Therefore, it would be efficient and judicious to maintain the relative humidity in a data center below the CRH of accumulated particulate matter to ensure the reliable operation of IT equipment and prevent its deterioration by electrical current leakages between the closely spaced features.

This method proves to be an effective method in determining the CRH and DRH of salts and overcomes the limitations of the other measuring techniques. The entire setup is cost-effective, very reliable and easy to handle. The process is also time efficient and one can obtain the DRH values of salts or dust quickly.

It can be seen from the linear graphs results of the dust samples collected from the servers of the research modular data center situated in polluted geographies of Dallas, the DRH values of particulate contaminants of this site are between 70-80%. To get an exact DRH value, we can create logarithmic graphs of the results which might then make it possible to get higher DRH value than that obtained from linear graphs as previously discussed in the results section. This can be the reason that we haven't noticed even a single server failure due to particulate contaminants from the research data center during its five years of continuous operation. The particulate contaminants found in this data center are ultra-fine particulates [16]. This study also supports the previous conclusions i.e., the DRH of fine particulate is not an issue for IT equipment reliability [15]. From the studies of [8], [16], [20] and this paper, it was noted that there had been no server failures in the test site due to gaseous and particulate contaminants. It is then recommended that this data center can be operated outside of the ASHRAE recommended envelope for an extended period taking advantage of free cooling.

6. FUTURE WORK

The INA219 current sensor used in this experiment is not a very precise device for measuring very small values of current and it has an input bias current of 20µA as well. In order to sense such a small value of current, an amplifier with extremely low input bias current is desired. Our future plan would be to replace the current sensor and to use a new current sensor which can give us a current measurement capability in the range of µA. The instrumentation amplifier with lowest input bias current is the INA116. It has a maximum input bias current of just 25fA. Another device that may be of interest (and perhaps easier to use with respect to PCB layout and package) is the INA121. The INA121 has a maximum input bias current of just 50pA. Note that these devices have relatively large offset voltages, so we will want to ensure that the minimum shunt voltage (product of minimum current and shunt resistance) is significantly larger than the offset voltage of the device. An alternate option is to calibrate out the offset voltage by supplying the circuit with a known precise current and subtracting the error. A potentiostat is the perfect instrument to measure the current with time-lapse.

Similar experiments can be conducted on samples collected from various data centers located in different geographies and establish the threshold operating RH% values specific to their location for free air cooling.

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