Experimental Investigation of the Effect of Atomizing Electrospray Nozzles on the Cooling and Reduced Humidification of Air.

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EXPERIMENTAL INVESTIGATION OF THE EFFECT OF ATOMIZING ELECTROSPRAY NOZZLES ON THE COOLING AND REDUCED HUMIDIFICATION OF AIR

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ABSTRACT

Separating sensible and latent cooling have shown the potential to reduce energy consumption in A/C systems for building HVAC applications. Several technologies exist based on vapor-compression refrigeration, enthalpy wheels, chemical adsorption and absorption materials, and mechanical cooling. However, their thermodynamics limits and high energy consumption hinder their deployment in hot and humid climatic regions. This paper focuses on separating sensible and latent cooling by using a new thermodynamics process and in-kind (i.e., non-vapor compression-based) technology. Highly electrically charged water droplets were sprayed in the airflow. These droplets attracted water vapor molecules to their surfaces and promoted condensation. The phenomenon was the result of simultaneous dielectrophoresis and electro-diffusion interactions. Studies in the literature have shown that using multiple capillary electrodes reduced air moisture by up to 5% when using nanometer-size droplets in the spray. Unfortunately, these studies were limited to low airflow rates, and the objective of this paper was to investigate how to scale up this in-kind approach to airflows typical of buildings. In the present paper, droplets of micrometer size were utilized to control the humidity for a 5-cfm flow rate. While this airflow was still low for building applications, it was 100 times fold the airflows in the literature studies. The air was tested at 20°C and at 50 and 80% relative humidity. A two-fluid atomizing nozzle produced the droplets in the spray, and high DC electric potential, up to 25 kV, was used to charge the fine droplets electrically. The air atomizing nozzle with high voltage potential resembled an evaporative cooler process. However, a measurable reduction of the absolute humidity of up to 2% was observed compared to the case of the nozzle with no high voltage potential. The entire device had one small nozzle selected from off-the-shelf components and had less than a 9 cm^2 footprint area.

1. INTRODUCTION

Today the buildings face environmental, economic, and air quality control challenges that demand innovative solutions for the HVAC systems. Designing thermal systems that consume less energy, provide adequate comfort, and are feasible to integrate into existing HVAC units, is key to achieving sustainability in the heating and cooling sectors of buildings. In 2021, electricity use for space cooling by the US residential and commercial sectors was estimated to be about 10% of the total US electricity consumption. (U.S. Energy Information Administration, 2022). Among HVAC largely used equipment, conventional air conditioning systems have revealed themselves to be less efficient because of the limited control of sensible cooling and latent cooling capacities, especially in some very hot and humid regions. They typically use mechanical cooling to remove moisture from hot and humid supply air. In these systems, the air temperature has to be decreased below the dew point temperature. However, the dew point temperature is usually lower than that required by the supply air. As a consequence, additional energy is spent to provide thermal comfort for the building occupants. Separating sensible and latent cooling (SSLC) AC systems by using separate devices has the potential to increase the efficiency of the system because (i) a reduced latent load on the evaporator coil and (ii) an increased coil dew point temperature.

Research was devoted on investigating ways for implementing the SSLC concept (LIng, et al., 2010). One approach consisted of humidifying a limited fraction of air using a vapor compression cycle or using a desiccant, and the remaining air is cooled to a temperature susceptible to meet the sensible load. With this configuration, it was possible to avoid the unnecessary reheat of air and save up a significant quantity of energy. Another promising alternative to avoid reheating unnecessary air is to use the potential of electrostatic assisted air dehumidification processes. Electrostatic spraying processes were used in many manufacturing industries such as aeronautics, nuclear, chemistry, oil, textile, automotive and biotechnology. It is now well known that highly charged water droplets have the potential to attract water vapor molecules to their surfaces and promote dehumidification by dielectrophoresis and diffusion. The physics underlying this process was well documented in recent years. Research dedicated on the implementation of this way of "wiping" air is still limited in scope; many are restricted to relatively very lower flow rates. Finding a way to scaling up this technique can be of further interest for implementing SSLC AC systems.

Spray nozzles have been widely used as indirect evaporative cooler solutions with the advantages of being refrigerant-free and low-energy-consumed cooling technology. The indirect evaporative cooler sensibly cools the air with the aid of water evaporation in the vicinity and it is found to be an ideal cooling solution for data centers. In this study, spray nozzles are used for their ability to provide very small droplets and the potential of these latter to attract polar water molecules when subjected to an external electrical field is investigated.

2. LITERATURE REVIEW

Several studies have shown that the presence of ions and electrically charged particles in carrier gas increases the condensation rate of the water vapor. These conditions can be obtained when the moist air passes through a zone with an ionized electric field (corona discharge). When a high voltage is applied, the air near the corona electrode is decomposed into cations and electrons. The electronegative gaseous molecules, including water vapor, O_2 and CO_2, capture the electrons and migrate towards the cathode under the electric field. These charged molecules in their flight to the cathode act or serve as nucleation centers. Kelvin equation, derived from Gibbs free energy of the liquid, is one of the fundamental relations used in homogeneous nucleation that quantitatively describes the change of vapor pressure for spherical liquid surface of radius R. This equation reads:

$$\frac{P_o^K}{P_o} = \exp\left(\frac{2\,\gamma V_m}{kTR}\right) \quad \textbf{(1)}$$

P_o^K is the vapor pressure of the curved, P_o that of the flat surface, γ is the liquid surface tension and V_m is the molar volume of the liquid. Considering a water droplet as nucleation center, due to the difference between the electric permittivity of the water droplet and surrounded gas, the electric field produces an electric double layer of opposite charges on the droplet surface that increases the induced dipolar momentum (interfacial polarization). When the droplet is electrically charged, the saturation vapor pressure decreases and was previously predicted as shown in equation (2)

$$\frac{P_o^K}{P_o} = \exp\left(\frac{2\,\gamma V_m}{kTR} - \frac{q^2 V_m}{32\,\pi^2 \varepsilon_o kTR^4}\frac{\varepsilon_w - \varepsilon_v}{\varepsilon_v \varepsilon_w}\right) \quad \textbf{(2)}$$

where ε_o, ε_w and ε_v are respectively the permittivity of the vacuum, the liquid water and the vapor water. The above correlation takes into account the interfacial polarization of water in the droplet and the vapor near this droplet. A further improvement was made by F. Yu (2005) considering the additional potential energy of drifting of dipoles due to high divergent electric field that arises when a neutral particle is submitted to an electric field (dielectrophoresis). Analysis of equation (2) and its subsequent improvement show that the chemical potential of a charged droplet is always lower than that of the vapor over the flat-water surface. As a result, the growth of these droplets is always thermodynamically favorable because this decreases the Gibbs energy of the system.
Reznikov and collaborators have conducted one of the most recent and prolific studies in the field of electrically enhanced condensation over a wide range of applications. Using a cooled multichannel steam condenser equipped with an array of corona wires, they were able to show that the performance of the steam condenser was improved by about 16% when products from ionized air serves as nucleation centers (Reznikov, 2015). Evaluating both positive and negative corona, the study reveals that the effect of the negative corona was less pronounced than what was observed with positive corona. However, the author believed that this outcome was inherently related to experimental

design conditions. Moreover, when electrospray injected micro-droplets were used as nucleation centers instead of ionized air from corona discharge (Salazar, et al., 2015), the performance of the steam generator was much higher (up to 57%). Electrospray micro-droplets are known to be more efficiently electrically charged than water vapor droplets capturing electrons from air ionization due to electric breakdown. In addition, the use of a pulsed electric voltage as a replacement for a constant DC voltage was found to be beneficial in increasing the condensational rate as water droplets acted as nucleation centers (Reznikov, 2003). The application of constant voltage was less effective, authors suggested that interval between voltage pulses allows the growth of droplets to bigger, more stable sizes.

Higashiyama and Kamada (2017) investigated the effect of nanometer droplets released by negative corona discharge from electrospray needles to wipe moisture from low-speed unsaturated air flow (70-90 % RH) using different gauges of needle. The investigation was successful in achieving a 5% reduction in relative humidity and emphasized the fact that, although negative ions produced by corona discharge from the needle electrode alone was surely effective to wipe moisture from air flow, the effect of dehumidification was significantly much pronounced when water droplets were injected from the needle electrode. The increasing dehumidification effect would be caused by the longer life time of water droplets during their flights compared to the low inertia of negative ions in space. Negative water droplets have a more chance to encounter moisture in air. In the same register, Dumitran *et al* (2017) improved the condensational rate and dehumidification efficiency of a simple air-cooled wire-cylinder condenser using corona discharge. From experimental investigations presented so far, only few of them focused on air humidity control. It is worth noting that ionization of air yields to ozone generation and this may become a matter of concern if the electrically enhanced condensation concept in its current development is foreseen to be implemented in air handlers for commercial and residential buildings. Cloupeau (1994) investigated the corona onset field in relation to Rayleigh critical fields for the electrostatic spray. The Rayleigh critical charge may be reached without the onset of a corona discharge for liquids of low surface tension. However, for water, the electric field of corona onset becomes smaller than the Rayleigh critical field when the radius of the jet was less than 162 microns. Morcelli and Cremaschi (2021) theoretically derived a set of conditions to produce droplets highly charged susceptible to reduce the moisture in the air while avoiding the appearance of corona discharge. In the above-mentioned studies, the analysis of electro-static assisted air-dehumidification and water vapor condensation is based on micro-droplets generated by ionization of air or electrosprayed jets. However, the work presented in this paper deviates from the above-mentioned studies in that here micro-droplets are primarily generated by breaking up of liquid film by compressed air using an atomizing spray whose body serves as an electrode of a high potential electric field. In the absence of the electric field, the size of ejected droplets spans over tens of micrometers (10 to 40 μm).

In a gaseous environment such as that provided by a spray nozzle and in the absence of an electric field, small droplets have a higher vapor pressure than large droplets, more liquid evaporates from their surface and this tends to condense into large drops. The bigger drops grow at the expense of the small ones, a process known as Otswald ripening (Butt, et al., 2003). However, it is expected that the presence of surface charges on droplets changes the continuous evaporative loss of material to a process punctuated with a series of convoluted disruptions. As the droplet decreases in size, the density of charge on the surface of the particle will continue to increase until finally one or more small highly small charged droplets are ejected and the initial droplet loses significant of its charge. This process is used in combustion to reduce the total vaporization time and in many electrospraying applications. Doyle *et al* (1964) observed that about 30% of the original droplet charge and about 1/20 of its mass for droplets of 60 and 200 microns of diameter size are taken away as a result of disruptions. The phenomenon explained by Rayleigh's criteria for charged droplet stability was within the accuracy of their observations. A droplet could subsist until 8 disruptions. Abbas and Latham (1967) investigating droplets of diameter sizes ranging from 60 to 400 microns found that convoluted disruptions of droplet resulted in the removal of about 25% of the droplet mass with about 30% of the electric charge. Standard techniques of charging droplets were developed through the years according to applications or desired level of electrification of droplets. The work of Law (Law, 1978) can be referred to for further information. In the current investigation, two particulate charging methods were considered: ionized–field charging and electrostatic-induction charging. The former method was largely discussed in previous sections while the latter one will be briefly explained in the next section The present study investigated how the combined effects of these charging methods of water droplets would contribute in the reduction of the humidity content of an air stream. Some current measurement was performed in order to evaluate how effective are these charging methods.

3. EXPERIMENTAL SECTION AND METHODS

The experimental setup consisted of an air flow system, a test apparatus, and measuring stations to evaluate upstream and downstream air flows psychometric conditions. A closed airflow wind tunnel with cooling coils, electric heaters, and steam generators controlled the air temperature, humidity, and speed entering and flowing around the test section apparatus. A second smaller airflow wind tunnel was installed inside the large wind tunnel, and it accommodated the converging duct where the working test section was mounted. The double-wall configuration minimized, if not eliminate, any heat leak to the air that circulated in the test apparatus.

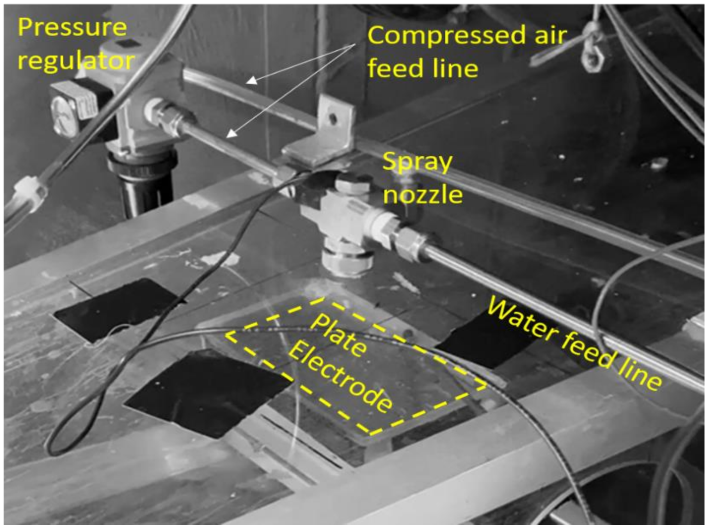

Figure 1: Photography of the test apparatus mounted over the small wind tunnel

Figure 1 is an illustrative photography taken inside the wind tunnel of the test apparatus mounted over the small wind tunnel where energized droplets were injected in air flow.

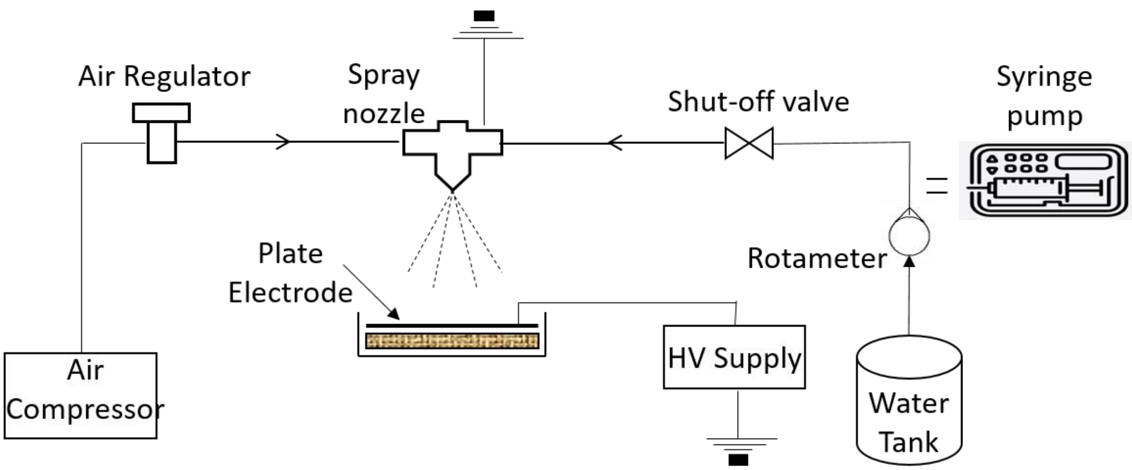

Figure 2: Schematic of the test apparatus

The test apparatus depicted in Figure 2 consisted of a two-fluid atomizing nozzle, a compressed air line, a water feed line, and a high voltage supply with associated electrical connections. Droplets were generated by a two-fluid atomizing nozzle in which a primary fluid was used to assist in the disintegration of liquid jet or sheet. The compressed-air line conveyed air from a compressor to the nozzle for breaking up of water continuous flow. With a relatively high velocity, air at 20 psi impinged at some angle onto a relatively low-velocity water stream under an external-mixing configuration to give a constant spray angle at all liquid flow rates and a round spray pattern. A Wilkerson knob-adjustable pressure regulator (maximum pressure 150 psi) was placed on the line to control the pressure line. The type of spraying nozzle used, BEX n°JPL1A with 0.406 mm orifice diameter, was selected. The compressed air flow siphoned from the liquid container which was located 12 inches below the nozzle exit. The mass flow rate injected through the nozzle was estimated by measuring the mass changes of the water container at regular intervals and using a scale with 0.01grams accuracy. Droplets of 10 to 40 μm diameter were estimated according to the nozzle manufacturer data for the testing conditions. Compressed air and water feed lines were made of metal stainless steel tubing. Subsequently, instead of a liquid siphoned system, water was fed to the nozzle under pressure using a New Era 1000 series programmable syringe pump with a 60 mL syringe capacity. For this case, a mass balance was regularly conducted between the volume displaced by the syringe barrel and the water delivered by the pump flow rate indicator, and pipe tubing was made of PVC. Unevaporated water droplets are collected in a container and measured using a high accuracy weight scale. Tap water was used as the liquid working fluid.

An external electric field is established with a pair of electrodes, a thin rectangular plate (0.78 mm thick, 122 mm length, 71 mm width), and the body of the spray nozzle. The distance between the rectangular plate and the nozzle was 6 cm, this distance should ensure that ionized-field charging took place. Throughout experiments, the nozzle body was grounded and the other electrode was connected to the cathode of a 5 kV-35 kV Universal power supply (voltage controlled). The positive electrode would induce negative charges on the nozzle body and droplets at the exit of the nozzle. Individual droplets formed from the negatively charged continuous jet (before droplet break up) would depart with a net negative charge. It should be noted that the level of charge acquired by the droplet during this phenomenon would largely depend on the relative time rate of charge transfer. Underneath the electrode plate, an absorbing foam material was used to avoid re-evaporation of falling water drops. Temperature and humidity measurements were made using respectively thermocouples and dew point meters. Measuring stations were located 40 cm upstream and 29 cm downstream of the apparatus test section.

4. RESULTS AND DISCUSSION

4. 1 Data reduction

It was experimentally observed that with the spray nozzle acting as an evaporative cooler (while water droplets were injected, a significant amount evaporated depending on the flow injected), the process that air underwent could be represented in the psychometric chart by one of these arrows presented in Figure. The slope sign of the representative curve depended on the temperature of injected droplets and the relative humidity of incoming air.

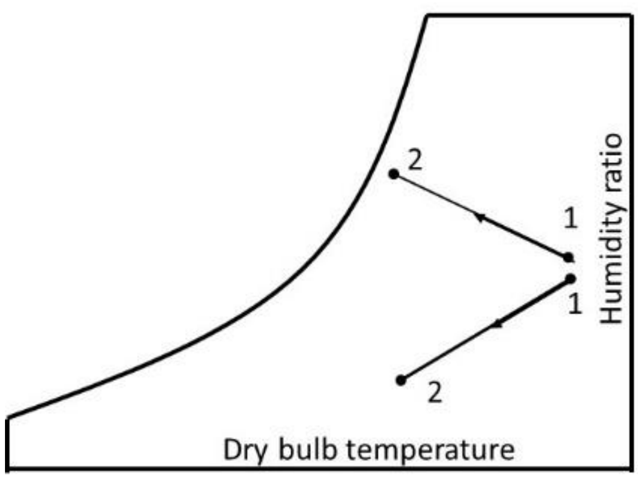

Figure 3:Psychrometric process of air with a spray nozzle

The upward arrow represented a typical process at low relative humidity (~50% RH) while the downward arrow exhibited the behavior observed at higher relative humidity (> 80%RH). For both cases, the effect of high voltage on the performance of the process was quantified by a parameter defined as Dehumidification Performance, $\Delta\omega^*$, and calculated as follows:

$$\Delta\omega^* = \left(\frac{\omega_2 - \omega_1}{\omega_1}\right)_{0\,kV} - \left(\frac{\omega_2 - \omega_1}{\omega_1}\right)_{HV} \quad (3)$$

Where subscripts 1 and 2 described respectively air conditions at inlet and outlet of test apparatus section. Therefore, $\Delta\omega^*$ is positive when there was a reduction in water content of air due to the presence of the electrical field and negative when the humidity of vapor content increased compared to the case when no high voltage is applied.

4.2 Experimental results

The purpose of this preliminary qualitative test was to explore how the application of an electrostatic field to injected water droplets affected the characteristics of moist airflow. The initial trajectory of injected droplets was orthogonal to airflow direction. Following parameters described operational testing conditions:

- Volumetric flow rate: 2.5 and 5 cfm
- Air inlet relative humidity: 50 % and 80 %
- Injected water flow rate: 0.3 to 1.2 ml/min
- Water injection method: syphon system or syringe pump
- High voltage supply potential difference: 8 to 25 kV

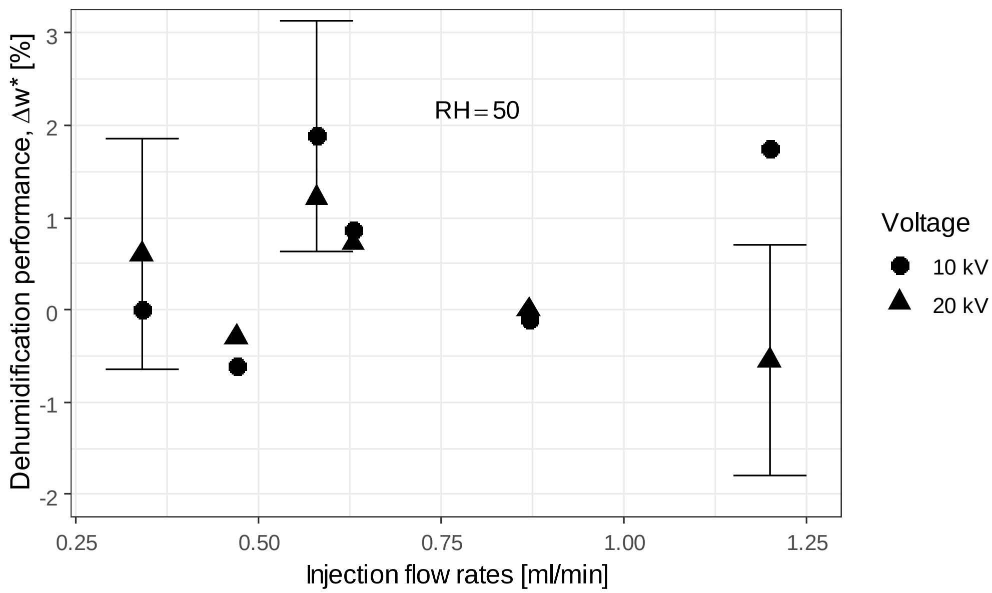

Figure 4: Variation of dehumidification performance as a function of injected water flow rates at 5 cfm (Syphon-injection system)

The dehumidification performance for different water injection flow rates with air inlet relative humidity of about 50% and volumetric flow at 5 cfm is presented in Figure 4. High voltage thresholds were limited to 10 and 20 kV. While the majority of data lied in what uncertainty analysis would assimilate to noise, test results at 0.58 and 1.2 ml/min with 10 kV departed slightly from the noise and reached about 2% of reduction in the humidity ratio for the electrospray with respect to the similar test condition with spray. The 20 kV potential did not significantly promoted additional electrical charges with respect to 10 kV. The overall experimental uncertainty in measuring the dehumidification performance Δω* was about 1.3%.

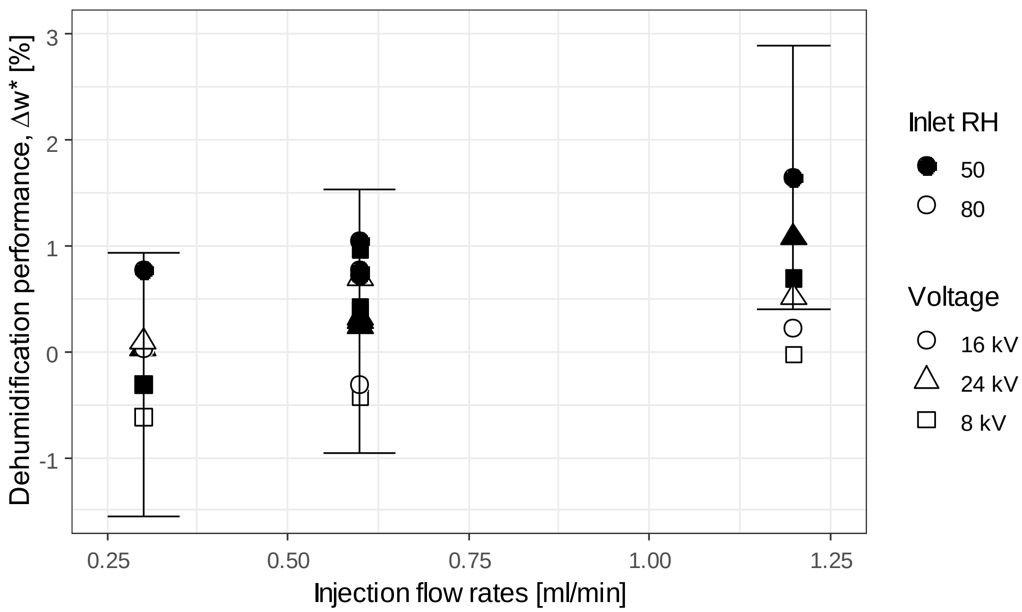

Figure 5: Variation of dehumidification performance as a function of flow rates at 5 cfm (Syringe-pump injection method)

Figure 5 is an illustration of the dehumidification performance when the injection of water by siphon at the spray nozzle was replaced by a syringe pump. Two different air inlet relative humidity were used 50 and 80 %. Overall, there seemed to be no improvement in the dehumidification performance as the injection method changed, on the contrary, a slight deterioration was observed. However, with injection water flow rate at 1.20 ml/min, the slight reduction in the humidity was still visible. Recall that the injection method could affect how the atomization process happened in the nozzle, it was expected that droplets slightly increased as the injected method changed from siphoning to pumping with a syringe. Comparing results at different incoming specific humidity, the enhancement in the reduction of humidity observed at 1.2 ml/min was no longer perceptible by increasing the air flow specific humidity from 50% RH than to 80% RH.

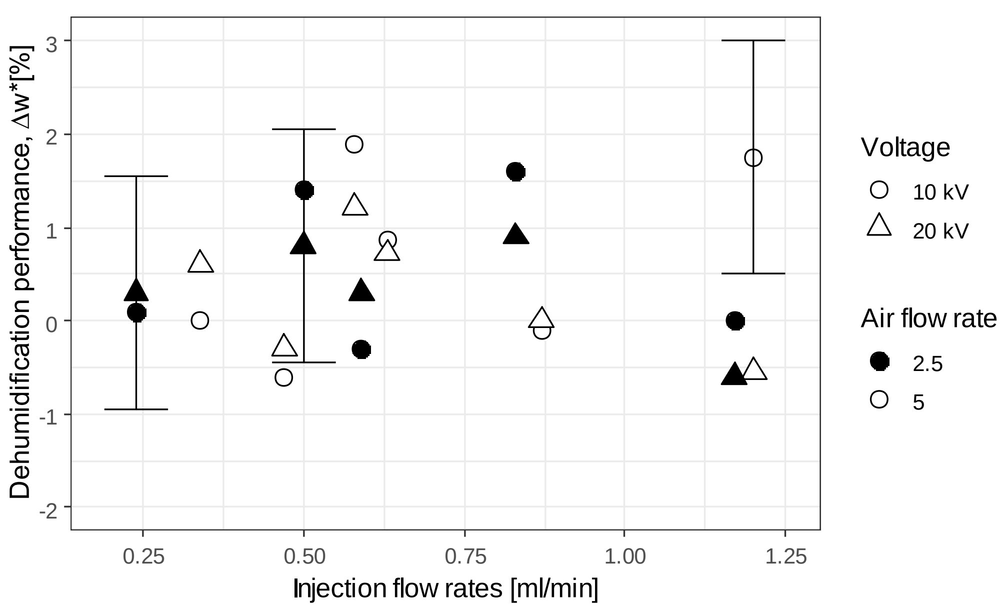

Figure 6: Comparison of dehumidification performance for different volumetric air flow rates, 2.5 and 5 cfm (Syphon system injection method)

In Figure 6, dehumidification performances with various voltages are presented for two different volumetric air flow rates, 2.5 and 5 cfm. When comparing at exactly the same injected water flow rate, for instance at 0.6 and 1.2 ml/min, dehumidification performance decreases as the injected flow rate decrease. On one hand, one could expect this to happen since when the volumetric flow rate decreases, the vertical component of the velocity that dictates the lifetime in the air duct decreased if the airflow was higher. In this case, there was a high probability that an electrically charged water droplet encountered more water vapor molecules during its flight trajectory. On the other end, as the flow rate decreased, the amount of water vapor to wipe decreased for the same quantity of charged particles. This should improve the dehumidification performance. However, from the observed results, the former effect seems to prevail over the latter.

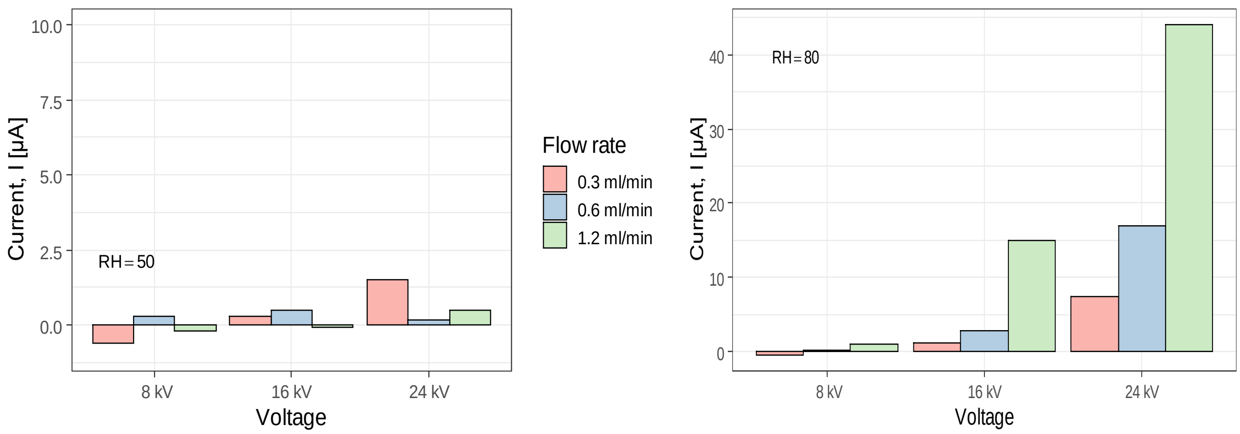

Figure 7: Current measurements at 5 cfm, nozzle coupled with a syringe pump.

Finally, measured dispersion currents are presented in Figure 7 (5 cfm, RH 50 and 80%, syringe pump). The averaged current reading was plotted versus voltages for different flow rates. During testing, it was observed a fluctuating current signal whose minimum and maximum values could have reached hundred fold the mean value. At first glance, it seemed that the averaged current increased with water flow rates and voltages and testing at high humidity provided relatively higher average current intensity but globally, these current were found inadequate for an efficient charging of droplets. Computing the average charge per unit liquid volume of the droplets defined as the ratio of the current measured from the spray (I) to the injected water flow rate (Q) and assuming an average size for water droplet diameter (20µm), a first approximation of the charge per droplet attained varies from 6% to 30% of the theoretical value that could be predicted by the Rayleigh limit (for higher flow rates at 8 kV). This is significantly lower compared to droplet charge levels attained with electrosprayed droplets. A more efficient way to charge the injected droplets has to be developed in future work.

5. CONCLUSIONS

The overall goal of this paper was to evaluate the potential of an energized two-fluid spray nozzle to capture water vapor molecules from a moist airstream. Electric charging principles included ionized-field charging and electrostatic inducing. While most of the data collected might lay in the experimental noise region, there was yet a clear indication from the overall test results that a net reduction of humidification occurred when electrosprays were used instead of conventional pressurized air-water spray nozzles. For some of the tests, the reduced humidification was up to 2% of the absolute humidity leaving the spray at an airflow of 5cfm. This is an encouraging finding when compared to the results available in the open-domain literature. Direct contact charging could improve performance, however, the maintenance of spray nozzle and the entire liquid handling system at an elevated voltage needs to be addressed in future work.

NOMENCLATURE

A/C	Air Conditioning	
SSLC	Separating sensible and latent cooling	
ω	Absolute or specific humidity ratio	kg/kg-dry air
k	Boltzmann constant	1.38066 x 10^{-23} J/K
$\Delta\omega*$	Dehumidification performance	%
q	Electric charge	C
ε	Electric permittivity	F/m
I	Electric current	μA
HV	High voltage	V
Q	Injection flow rate	ml/min
V_m	Molar volume	m^3/mol
R	Radius of liquid droplet	m
RH	Relative humidity	%
γ	Surface tension	N/m
T	Temperature	K
P_o^K	Vapor pressure on curve surface	kPa
P_o	Vapor pressure on flat surface	kPa

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