Water Aerosol Sensor exploiting Projected Electric Fields

Abstract

In this paper a capacitive sensor and system for the detection and measurement of water aerosol and droplets deposition is presented. Unlike humidity sensors that are designed to detect gaseous water in air, few devices are designed to detect actual water aerosol. The presented invention can provide a quantitative measurement of the amount of water an aerosol contains exploiting projected electric fields. The sensor can be used either to be stuck on a surface to monitor the build-up of water droplets on its sensitive surface due to condensation, or suspended in air to measure the concentration of liquid water suspended in air or other gases.
A further embodiment of the invention provides for a system for multiple measurements with a single processing unit to gather information on wider surfaces or multiple points.
Applications comprises the prevention of the growth of molds and fungi in buildings, wood structures, farms, food and crop storage, warehouses; the prevention of the build up of rust in tool storage; the prevention of oxidation and "popcorn effect" in electronic components; to warn in the case of water condensation in sensitive machineries; in industrial processings.
The sensor proved to be sensitive enough to detect even the droplets ejected when breathing hard on it, characteristic that went useful in a comparative test for the effectiveness of face masks.
Results from the experiments performed show a proportionality of the measured amount of water particles in the aerosol at the proximity of the sensor.
While the cheap solution does not provide shielding on interfering dielectric on the back of the sensor, those interferences can be easily compensated in the processing unit at the set up stage, providing a cost effective solution for direct monitoring of water aerosol in place of combining humidity and temperature sensors and a processing unit to estimate the dew point.

Introduction

Water condensation on surfaces is a phenomenon that, depending on circumstances and applications, can be a desired or unwanted effect. While psychrometric devices can provide information about the thermodynamic properties of the water vapour-air mixture, few devices are available to detect and quantify the actual build-up of dew droplets on surfaces. Even less are capable to quantify the concentration of liquid water in an aerosol, that is when relative humidity goes beyond 100%.

In this paper is presented a sensor that can be used in two ways. One is the detection and measurement of the concentration of liquid water particles in air (or other gases) when the sampled aerosol reach the proximity of the sensor. And an other one is the detection of water condensation on a specific surface by attaching the sensor itself to that surface.
In the first possible application, the sensor is kept floating in air (or other gas under test), so that the sensor reaches a thermal equilibrium with the gas under test. In the case of air this allows the measurement of the amount of water even beyond 100% of relative humidity.
In the second possible application, the sensor is attached to the surface for which it is important to know when humid air would condensate its water content on such a surface because colder than the surrounding air, despite the air is far from its dew point. This is possible because the sensor reaches the thermal equilibrium with the surface on which is attached to, therefore causing the water in air to condensate in the same way it would on the remaining surface to test.

A further development is a system composed by a plurality of sensors that can be connected to a single processing unit to provide multipoint measurements.

The sensor exploits a well known capacitive effect, generating a projection of electric fields from a grid (or network) of electrodes, detecting the capacitive interaction of water particles with said projected electric field.

Capacitive sensing is a well known technology in the state of the art. Proximity and touch sensing have been developed using open plate capacitors[1], with circuits that are based upon frequency deviation[2] or upon frequency excitation such as the one integrated in the FDC1004 produced by Texas Instruments[3].

Even though the sensor described in this paper has same apparent similarities to the one existing in the prior art, the controlling circuit is based upon a constant supply of charges rather than frequency deviation of an oscillator or amplitude detection through frequency excitation.

It can be considered therefore a novel approach to detect the proximity of particles or even bodies.

One possible application is the measurement of water condensation on buildings' surfaces, where multiple points can be monitored at the same time at regular intervals. Similarly, can be used to detect the condensation of water in machineries and to prevent rust as actual liquid water particles are the major cause for the development of ferric hydroxides (commonly known as rust).
An other application is to monitor the build-up of condensed water on stocked goods on multiple shelves in warehouses to prevent the growth of molds.
A further application is the control of the amount of liquid water particles suspended in air in industrial processing, such as in some leather and chemical processes where a very fine mist is sprayed, or to prevent the growth of molds and fungi in crop and food storage.

Because a plurality of sensors may be required in some applications, the sensor is designed to be cheap, outputs a robust signal, and requires as little as possibile wirings.

Description of the sensor, and the measurement system

The sensor is composed of a sensitive area and a control circuit. The measurement system is an external unit that can even host a plurality of sensors.
The sensitive area of the sensor is made with a grid (or a network) of electrodes. Each electrode has a very thin area that face the next, of opposite polarity electrodes, while featuring a much larger area toward the volume above the sensitive area.
The electrodes are then laid upon a comparatively thick substrate featuring very low dielectric coefficient, while on top they are protected with a thin, low dielectric, insulating agent.
The grid of electrodes can be arranged in a comb pattern (figure 1) or in an alternative embodiment in a network of pads (figure 2).
It should be understood that the patterns shown in figures are only a couple of examples of the possible designs, since different layouts produce different sensitivities and selectivity.

When charges are supplied to the electrodes these generates electric fields that are predominantly forced to be projected outward the sensor's surface, above (figure 1, b) and below it. The projection below is neutralized by the action of the substrate, while the projection above can interact with the air or other gas in which the sensitive area is exposed to. If any particle is suspended in such a gas or air, that particle will interact with the projected electric field as well. This interaction causes the build up of charges making the particles themselves part of a compound mutual capacitance. Depending by the dielectric permittivity of said particles, the capacitance will vary, causing the accumulation of charges supplied through the projected electric field to vary as well.

With reference to the figure 3, in the control circuit a constant source of charges (1) is attached to one poles of the grid of electrodes that form the sensing capacitor (2). This provides a controlled, progressive amount of charges to the electrodes, and said accumulation of charges depends on the dielectric characteristic of the substance that is in very close proximity, or actually in contact with, the surface of said sensing capacitor. An amplifier picks up the voltage created by this progressive accumulation of charges and its output is connected to a comparator (4) that trips at a given reference voltage. The more the dielectric permittivity of the material compounded between the electrodes the more the time required to raise the voltage as in equation 1. Once the comparator detects the defined level of voltage it drives a pulse generator that in turn drives a transistor (5) that pulls down the sensor's output for a fixed “hold-on” time (8), and a sequenced second fixed delay “discharge” time (7), that keep the transistor (3) on.
Shorting the power supply line allows the transmission of the information back to the processing unit (9) using just one wire[4] (unlike the cited expired patent in [4] the information here is width

modulated though.)

The delays have three functions: they provide a stable discharge point, they prevent the sensor's power supply capacitor (6) to discharge excessively, and they provide a time reference for the remote processing unit (9) to check against the “charge time” signal width.
The ratio between this fixed hold-on time and the variable charge time that is proportional to the sensing capacitance, that can be used by the processing unit to reliably decode the information using a low impedance strong signal.
Hence, the width of such pulse is proportional to the time required by the charges to accumulate on the electrodes of the sensing capacitor, thus it is proportional to the capacitance according to equation 1.

The system can be completed with a processing unit (9) that, in a possible embodiment may also comprises a multiplexer (11) at which several sensors (10) can be connected through a resistor (12). The multiplexer is controlled by a microcontroller (13) that also read the signal width from each sensor.

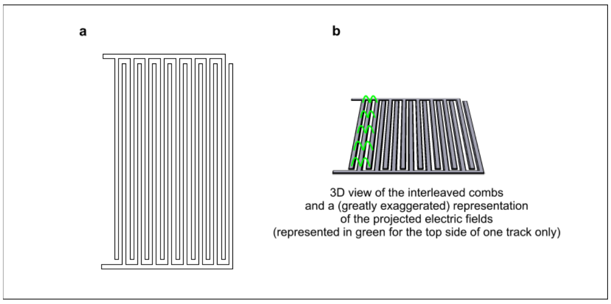


figure 1

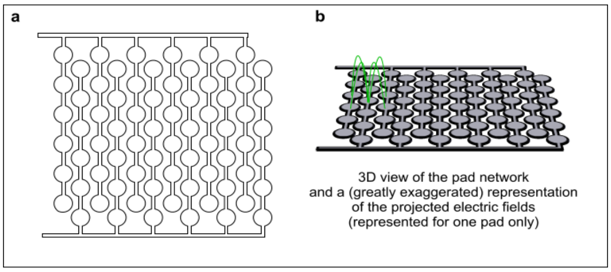


figure 2

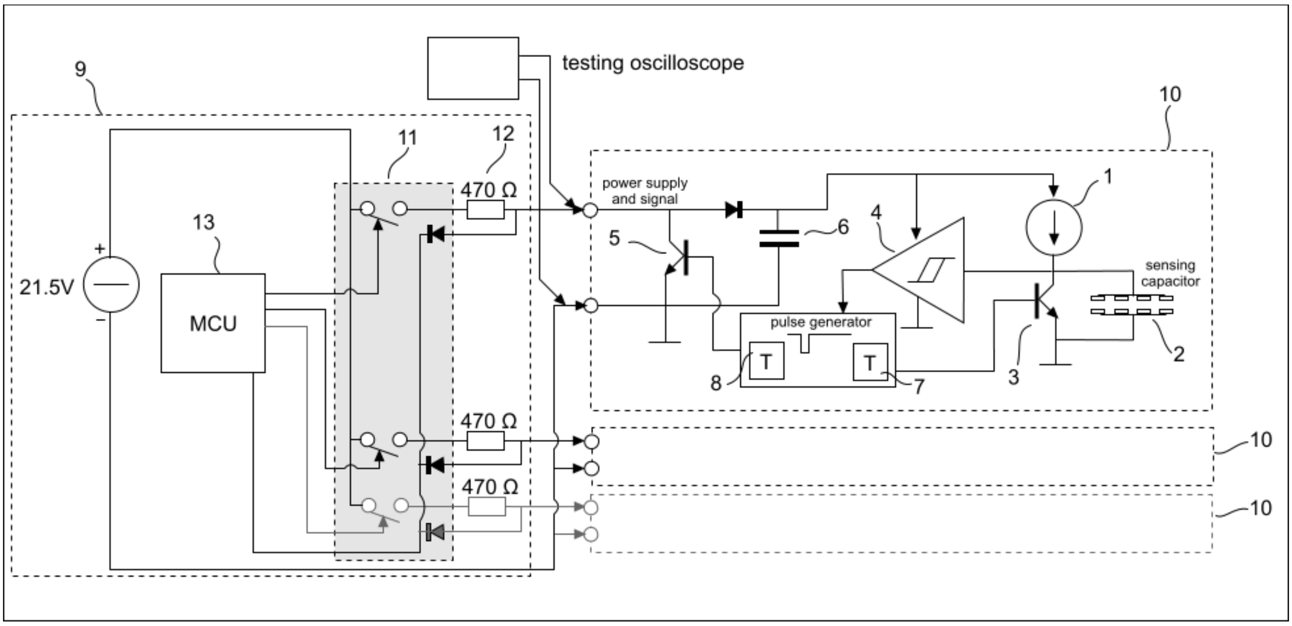


figure 3

Mode of operation

When a substance goes in proximity or in contact with the sensing surface, replacing the air, it changes the overall relative permittivity of the sensing capacitor. Specifically, when water comes within the projected electric field generated, the relative permittivity at that particular point changes from

$\varepsilon_r = 1$ of the air to $\varepsilon_r = 80.2$ (@ 20°C) of the water.

The particle sports a self capacitance that combines with the other capacitances: more particles and the electrodes.

This increase in relative permittivity causes an increase in capacitance that in turn, given the constant current source, increases the time required to reach the threshold voltage at the comparator (4).

equation 1:

$$t = \frac{C\,V_t}{I_s}$$

I_s: current source (constant);
V_t: threshold voltage (constant);
C: capacitance;
t: time

When the sensor is stuck on a surface of an object to monitor (e.g., a wooden beam) it reaches the same temperature of that object, and if the conditions determined by temperature, relative humidity and pressure of the surrounding air, and the temperature of the object to monitor, lead to the condensation of the gaseous water contained in air, droplets of water start to accumulate on the sensor's surface.

Similarly when the sensor is kept floating in air (or an other gas), and a water aerosol or mist is present, the particles that come into the projected electric field can be detected.

In both cases the sensor's self heating could induce evaporation of the droplets on its surface, or through irradiation, it could induce the evaporation of the water particles in its proximity.

It is therefore important to keep this effect as low as possible.

To accomplish this the microcontroller (13) can provide power to the sensor, or each attached sensor in the case of multiple sensing, for a short duty cycle, greatly reducing the sensor's self heating interference. Thanks to the single wire that carries both the power supply and the signal this operation is simplified, the assembly less cumbersome, and the whole equipment cheaper.

For the purpose of testing the sensor an oscilloscope is connected to a sensor under test, and the processing unit programmed to run the sensor for a long duty cycle making the sensor to generate a continuous frequency for the duration of the duty cycle.

The collected data is based on the frequency resulting by the sum of the hold-on time (fixed) and the signal pulse time, proportional to the capacitance, see figure 4.

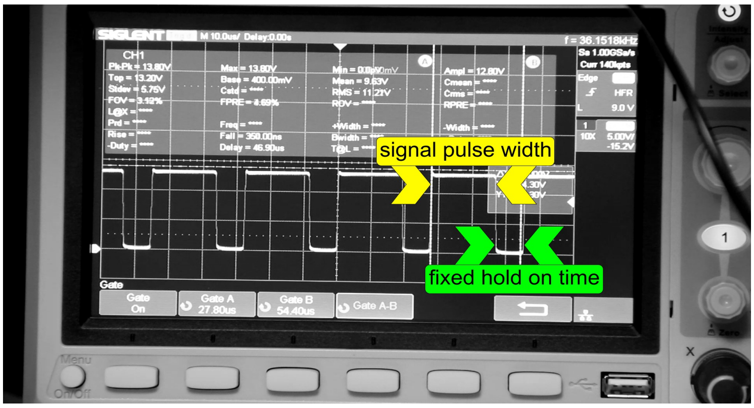


figure 4

Determination of the length of the protruding electric fields

The electric fields depart from the electrodes toward the space above and below them (see figure 1, b).
The determination of the length of these fields is demonstrated by the following experiment: above the sensitive area a flat grounded plate is moved from top to bottom toward the sensor, the motion is stopped as soon as a change in frequency larger than 10 Hz is detected (see figure 5). This deviation in frequency is chosen because it is the maximum resolution attainable free of noise.
The experiment demonstrated that the given deviation in frequency is produced when the plate reaches a distance of 5 mm from the top side of the sensor's sensitive area, hence it is inferred that the fields protrude from the surface for almost 5 mm.
This distance could change with a different pattern design of the electrodes, and a different design in the circuit including the components used and the very same layout of the circuit.
In some prototypes the layout was not good enough resulting in less accurate voltage progression and worst overall sensitivity and protrusion of the electric fields.

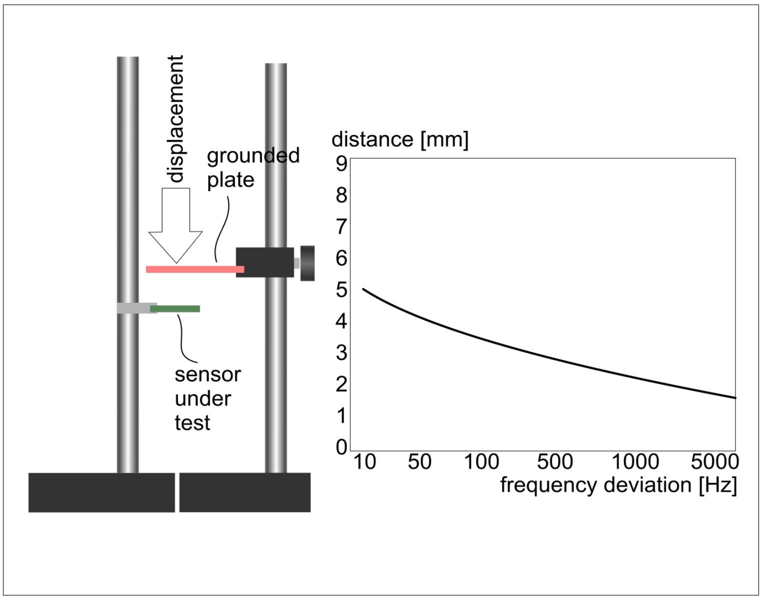


figure 5 – Remark: distance Vs. frequency varies with the electrodes pattern design.

This also leads to the conclusion that the fields that protrude below the sensitive area can influence the reading if the electrodes are obtained from a standard PCB with a substrate thickness of 1.6 mm.

Since the capacitance is affected by the area of the capacitor's electrodes and by the dielectric that influences the electric field, a change in capacitance due to the deposition of water depends on the sensitive area covered by water. In addition, since the capacitance have electric fields that protrude from the electrodes into the space, the capacitance is also affected by the thickness of such a layer of water.

To prove this a couple of tests are performed (for details about the procedure see Appendix A).

On one test drops of demineralized water are delivered separately on the sensor's sensitive area; on a second test the drops are delivered in a way that they overlap each other to form a larger drop.

On the first test each drop have a height of 1.4 mm and covers an area of $32mm^2$ on average, covering a total area of $193mm^2$ with six drops; on the second test the single drop formed by incorporating six overlapping drops have an height of 1.9 mm and covers an area of $127mm^2$.

The data show an increase in capacitance remarkably larger in the large single drop, despite the covered area is smaller.

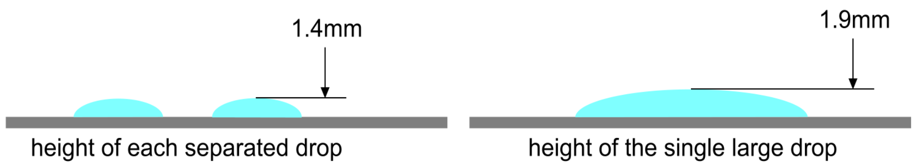


figure 6

The two tests highlights a linear change in capacitance that is proportional to both the area covered and the thickness of the water layer. In fact each one of the separated drops have a thickness that is smaller than the thickness of the single larger drop (figure 6).

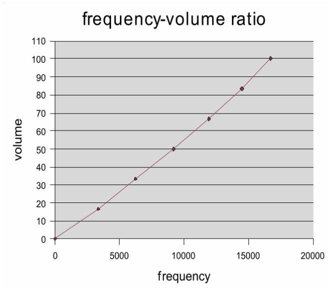
The resulted data show that a single drop with smaller surface area, but thicker, produces a larger increase in frequency deviation (thus in capacitance) than the thinner drops that in sum cover a larger surface area.
This is also highlighted by the output frequency to volume ratio (see table), as the final volume of the six drops is the same, but the effect is different due to the differences in covered area and thickness.

Results for the two tests: one involving six separated drops, and the other involving six overlapping drops:

Remark: the reported data are an average of three repeated tests.

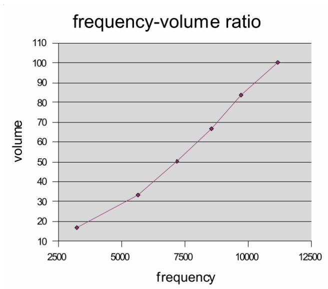
Multiple separated drops, each drop covers an area of 32mm², on average, with a total area of 193mm² for six drops.

number of drops	f base [Hz]	f test [Hz]	delta f	volume of water	frequency volume ratio [Hz/µL]
0	36488	36488	0	0	0
1	36488	33155	3333	16,7	199,58
2	36488	30255	6233	33,4	186,62
3	36488	27297	9191	50,1	183,45
4	36488	24554	11934	66,8	178,65
5	36488	22001	14487	83,5	173,5
6	36488	19774	16714	100,2	166,81



Overlapping drops, six drops covers an area of 127mm²

number of drops	f base [Hz]	f test [Hz]	delta f	volume of water	frequency volume ratio [Hz/µL]
0	36395	36395	0	0	0
1	36395	33161	3234	16,7	193,65
2	36395	30740	5655	33,4	169,31
3	36395	29203	7192	50,1	143,55
4	36395	27840	8555	66,8	128,07
5	36395	26680	9715	83,5	116,35
6	36395	25230	11165	100,2	111,43



Decrease in frequency shows an increase in capacitance. The frequency to volume ratio provides an outlook of the relation between the volume of water and the related increase in capacitance.

Determination of the amount of condensed water

A final test is performed to try to quantify the amount of water deposition from an aerosol or water vapour condensation in relation to the increase in capacitance.

To carry on this test an ultrasound aerosol machine is used. Under microscope observation the generated droplets have a size comprised between 50 to 170µm when impacted on the microscope's glass slide.
The machine is used to deliver the aerosol on the sensor's sensitive area to acquire the relationship between the generated frequency and the amount of detected water.

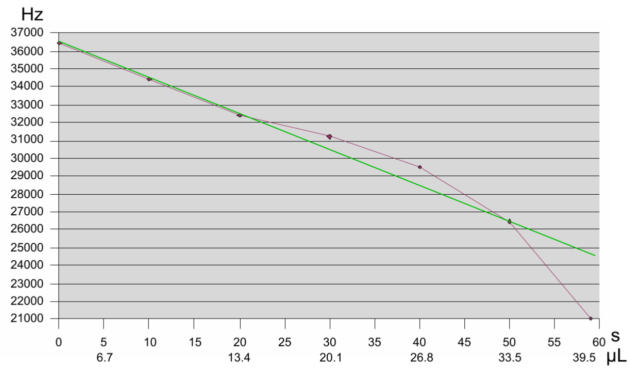
Please refer to Appendix B for details about the used method to determine the amount of water the aerosol machine delivers.

The result is a linear increase in capacitance for the first 33 µL, after that point the increase is no longer linear as the droplets start to stick on the surface and aggregate in larger drops that significantly increase their height causing a distortion in the measurement.

continuous flow of aerosol over time

time [s]	frequency	difference	µL
0	36450	0	0
10	34435	2015	6,7
20	32400	2035	13,4
30	31213	1187	20,1
40	29509	1704	26,8
50	26469	3040	33,5
59	21012	5457	39,53

µL every 10 sec 6,7



Conclusions

The ability to detect water droplets from condensation deposition or aerosol proximity exploiting projected electric fields and the dielectric deviations on capacitive of the sensitive surface has been demonstrated with success.
While further work would be necessary to determine the relationship between the deposited water, the amount of liquid water particles, and the output signal with greater precision, the viability of the solution has been demonstrated and some major findings show that:

1) the relationship between the amount of water and the generated signal shows a linear response within the range of the intended measurement (number of drops, cumulative overlapping drops, accumulation of water by deposition);
2) said relationship shows linear response even in the case of water particles suspended in an aerosol detected in proximity of the sensor's sensitive area, up to the point where the concentration is so high that droplets of water start to coagulate on the sensor's surface where the relationship start a transition from which a new linear relationship begins.
3) The sensor is sensitive to both thickness and covered area of the layer of water, thickness has a major role in determining the dielectric deviation, this also may cause a distortion in the resulted measurement in the case of droplet aggregation that produces an increase in thickness of the layer of droplets when measuring aerosol deposition or water condensation composed by tiny droplets.
4) The protruding electric field can be sensed at a distance of 5 mm for the given pattern of electrodes. To avoid complexity in the circuit and costs a simple compensation is performed in the processing unit to neutralize the constant dielectric of the underlying sensitive area substrate.

Appendix A

Procedure to determine the amount of a water drop dispensed through a syringe.

Even though a study has been made to find out the drop volume dispensed by a syringe[5], an experiment has been made to gain an insight into the actual dispensed volume of water through a modified syringe. The result of this experiment is congruent with the data mentioned in the paper cited above.

Six drops of demineralized water are delivered on the sensitive surface of the sensor by the mean of a modified syringe.
The drops are delivered through a 22G needle on a 2.5mL syringe containing demineralized water. The syringe is used without the plunger, and a flexible cap having a 3mm hole is put on its place. That hole is kept closed with the aid of the thumb while holding the syringe. Pressing the cap, the syringe so arranged dispenses a drop having a consistent size of 16.7µL ±1.1µL.
The size of each drop is calculated by counting the number of drops required to reach 1g on a precision scale:

Scale resolution: 0.01g
Density of water: 1g/mL
Number of drops in 1g: 60 ±4 drops
Volume per drop: 1000µL / 60 = 16.7µL (max 17.8µL; min 15.6µL)

Appendix B

Procedure to determine the amount of water delivered by the aerosol machine used in the experiment.

To quantify the amount of droplets delivered by the machine a piece of absorbent paper is used, cut to match the size of the sensitive area of the sensor (22 x 23 mm). While the absorbent paper is dry it is weighted on a precision balance (0.01 g resolution).
Then the machine is started to deliver the aerosol and the paper let to absorb the water from the aerosol. After 10 seconds, and then at intervals of 10 seconds, it is weighted again multiple times to see the amount of absorbed or anyway loaded water on the piece of paper.
The result is an increase of 6.7 mg ±3.3 mg every 10 seconds of generated aerosol.
Because the machine generates aerosol from a reservoir of demineralized water, this also means the machines covers the sensitive area with 6.7 µL ±3.3 µL every 10 seconds of operation.

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