MICRO GROOVED SURFACE IMPROVE DEW COLLECTION

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ABSTRACT

This work presents an experimental study on the atmospheric water condensation on micro-grooved substrates. The influence of several physical and geometric parameters (relative humidity, substrate inclination with horizontal, groove size) on the process of condensation and drainage is presented. The process is studied by weighing collected water and visualizing the drops formed on the substrate. The grooves appear to markedly increase the collected amount of water by promoting drop coalescence and lowering pinning forces, resulting in early shedding when compared to a smooth surface with same wetting properties.

INTRODUCTION

In many regions of the world, dew water could serve as an additional water source, supplementing rain and fog water collection. This can be particularly useful when precipitation is low or lacking. Unlike fog-catching nets specially designed to gather water from droplets in the air, dew condenser develops through radiative exchange with air a cooling surface that can condense water vapor when the dew point is reached. This method has the advantage to be used in many parts of the globe, which is not the case for fog nets, limited to specific regions (coasts and mountains).

However, dew collectors developed till now offer low yields of collected water (often <0.3 liter/m^2/night). Indeed, the amount of water collected is limited by the runoff of drops which remain attached by pinning forces. These non-collected drops evaporate in the morning when the first rays of the sun appear.

To reduce this limitation, we recently proposed [1] the use of geometric or thermal discontinuities that appear on the top of the condensers. The droplets near discontinuities can get more vapor than those in the middle of the surface which have to compete with each other, resulting in faster growth. Discontinuities indeed increase the water vapor gradient around drops, causing growth rate enhancement. Drops can thus rapidly reach there the critical size (~ mm) where they detach from the support by gravity. This phenomenon is quite interesting for droplet collection because drops that detach from edges act as natural wipers to scrape off the other droplets on the surface.

Another approach inspired from biomimetic material is proposed here to increase the yield of water harvested. Several papers [2-5 for example] have shown recently that bio-inspired surface dew water can be harvest by certain cacti or some beetles and lizards which live in arid environment thanks to their textured surface. In the same way, we propose micro-grooved surface to promote the coalescence of droplets and increase the dew water harvesting.

This paper presents an experimental investigation on micro-grooved substrates developed without surface treatment. Condensation is induced by placing the substrate at a temperature below the dew point. Influence on the process of condensation and shedding is presented by varying the physical parameters (relative humidity, inclination of the substrate with respect to horizontal) and the groove geometric characteristics (width, height, separation).

NOMENCLATURE

RH	[-]	relative humidity
h	[m]	groove depth

g	$[ms^{-2}]$	gravitational constant
r	[m]	drop contact line radius
s	[m]	groove channel width (groove separation)
v	$[m^3]$	volume
w	[K]	groove plateau width
a	[m]	drop width
b	[m]	drop length
T	[K]	temperature

Greeks symbols

α, θ	[deg]	tilt angle
γ	$[Nm^{-1}]$	surface tension

Subscripts

av	advancing
r	receding
p	wall

EXPERIMENTAL METHODS

Condensation experiments were carried out in a temperature and humidity-controlled environmental chamber. A schematic diagram of the experimental facility is shown in Figure 1. The substrate holder is a 2 mm thick stainless square steel plate of 173.2 × 173.2 mm size, screwed and pressed with thermal grease on a electrolytic copper plate of same size in contact with a Peltier element thermostat. The substrate of 70 × 70 mm is mounted on the cold plate of the Peltier cooler. The substrate surface temperature is maintained below the dew point by setting the Peltier cooler at 4°C. Thermal contact between the substrate and the holder is ensured by a small layer of thermal grease. Different tilt angles (α=15°,30°,40°,60°,75°,90°) will be considered.

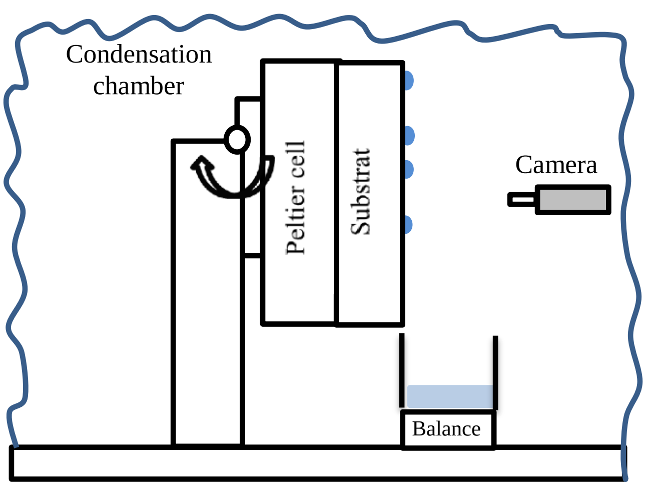

Figure 1 schematic representation of the device

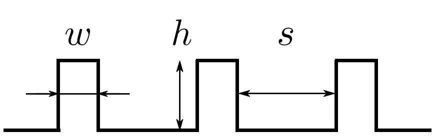

Figure 1 schematic representation of the substrate and associated notation.

Dew condenses from chamber ambient air whose temperature T_a and air relative humidity RH is constant during the experiment time within ± 0.5 °C and ± 3%, respectively. In the present work, experiments are performed at five relative humidities (RH = 30%, 40%, 50%, 60%, and 70%). The humid air is maintained at 33°C and ambient pressure. The substrate temperature is measured by a thermocouple taped on it. The growth process of droplets is observed from above with a high resolution CCD camera connected to a computer. This camera is equipped with a Pentax Megapixel lens with a 14 mm focus length giving a magnification of 42 px/mm. The images of the droplets are then analysed with an image analysis software (ImageJ) to obtain the size of the droplets in a given image area.

Usual microfabrication techniques are employed to produce substrates (silicium wafer) grooved to form a strip pattern structure of width 'w', separation 's', and height h (see Fig. 2). Substrates with 30-500 micrometers in spacing and width and 50–150 micrometers in depth have been realized.

The manifold consists a strip of fabric, positioned at a distance of 100 microns from the bottom of the substrate. A recording of the mass of water recovered is achieved throughout the experiment thanks to balance accurate to $1/10^{th}$ of a mg. The contact angle of a drop of water on these substrates is of the order of 50 °.

EXPERIMENTAL RESULTS

Figure 3 shows an image obtained on a grooved substrate (left side) and smooth substrate (right side) after 1 hour of condensation. The geometrical parameters of the grooved surface are $s = w = 100$ µm, $h = 65$ µm. Relative humidity RH, and temperature, T, of the chamber are respectively 40% and 33 ° C. The surface of the substrate is maintained at $T_p = 4$ °C. One can observe that the drops on the grooved substrate are less numerous and significantly larger than on the smooth substrate. Since the thermal resistance of the smooth and grooved surface are similar, this result cannot be attributed to a difference of heat flux or vapour flux. It cannot be attributed either to edge effects as the thermal and diffusive boundary layer, on order a few mm [1], is much larger than the groove depth. The origin of this phenomenon is the texture of the substrate that promotes coalescence between droplets and their shedding. The increase of coalescences with micro-grooved surfaces on horizontal substrates has been observed by Nahre & Beysens [6]. It corresponds to the coalescence of water droplets that forms on the plateau between the grooves and move towards the channel filled with water with which they merge. This random-like motion of droplets is induced by the coalescence events themselves [8].

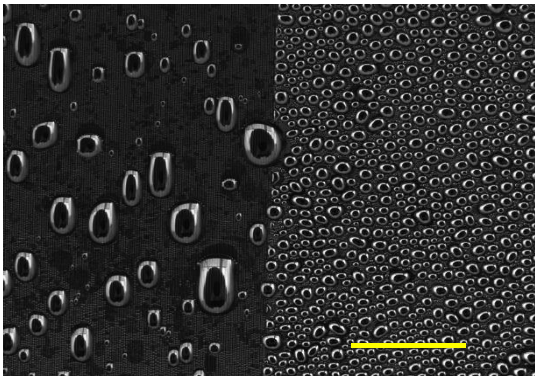

Figure 2 Picture of grooved surface in the vertical direction (s = w = 100 µm, h = 65 µm, left) and the smooth surface (right) after one hour of experiment, *RH = 40%, T = 33 °C*, and $T_P = 4$ °C (scale: 1cm).

When the substrate is tilted (α > 0 °), the drops slide after they reach a critical size of about a few mm^3. The drops are then collected by the collector. Figure 4 shows an example of the evolution of the collected water mass for two grooved pattern structures, $s = w = 100$ µm and $s = w = 300$ µm with same height $h = 65$ µm. For the different micro-grooved surfaces studied, the collected mass of water shows a linear variation with time; we remark that the start of drop shedding depends on the geometrical aspects of the texture. We note $t_\downarrow$ the time corresponding to the first drop of water collected. Dotted line in Figure 4 indicates the evolution of the mass of water attached on the smooth surface of reference (with same dimension as the grooved surface). It is thus possible to deduce the mass of water that does not flow and remains not collected between the initial time and time $t_\downarrow$. On grooved and smooth substrate of 20cm^2, condensation rate is 0.14 ℓm^{2}h^{-1} (interrupted line in Fig. 4).

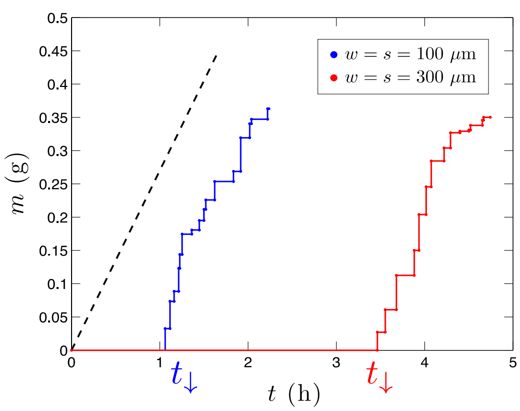

Figure 4 Evolution of collected mass of water for 2 micro-grooved surfaces with same height *h*= 65 µm, and for s = w = 100 µm (blue), and s = w = 300 µm (red), in the same condition as Figure 3; The first drop is collected at time $t_\downarrow$. Interrupted line is effective condensation without accounting for collection. It is determined on the smooth surface by drops imaging and weighing of water collected by an absorbing stamp.

Drops do not flow from the smooth surface for at least 5h. During that time, no water was collected from smooth surface. Extrapolation to 10h night assuming that water starts to flow after 5h on the smooth surface gives a value < 0.14×(10-5)= 0.7 ℓm^{2}h^{-1} (smooth) and 0.14×(10-1)= 1.26 ℓm^{2}h^{-1} (groove), that is at least a factor 2 gain for the grooved surface. Comparison with natural dew (typical condensation rate 0.03 ℓm^{2}h^{-1} for a 10h. night) corresponds to a factor 1/4.6 with the present experiment condensation rate. Waiting time for grooves would be about 4.6×1h.=4.6h. and more than 5×4.6=23h. for smooth substrate. No water drops would have been collected with smooth substrate.

Influence of relative humidity *RH*

Figure 5 shows the run-off time of the first drop as function of RH. This result is obtained for a substrate with $s = w = h =$ 65 µm, α= 45 ° and chamber temperature T = 33 ° C. For RH <50%, more humid is the air, more quickly the drops slide and are collected. Here relative humidity HR controls supersaturation and thus drop growth. For RH> 50%, the influence of this parameter becomes weak, because the rate of condensation becomes now limited by the cooling heat flux available by the substrate holder.

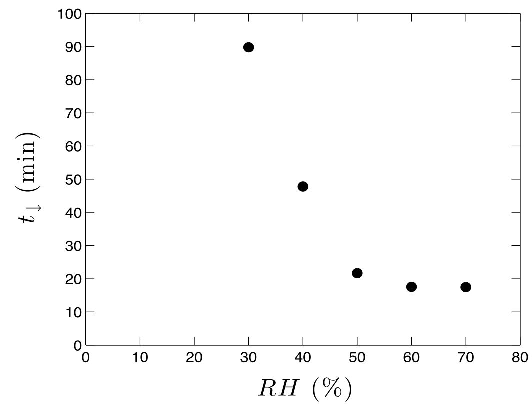

Figure 5 Start of run-off time as a function of RH for α = 45°, s = w = h = 65 µm and T = 33°C, T_P = 12°C.

The drop remains attached to the surface until surface tension forces are greater than gravity forces, which is reflected by the following inequality (see e.g. [7]):

$$\pi\, r\, \gamma\, (\cos\theta_r - \cos\theta_{av}) \geq \rho\, v\, g \sin\alpha \qquad (1)$$

Here r is the radius of the contact line of the droplet (supposed circular here), γ, the surface tension, ρ, the drop density; v is the drop volume , θ_{av}, the advancing contact angle, θ_r, the receding contact angle and g, the gravitational constant. The condensed drop detaches and slides as soon as it has reached a critical volume that varies as:

$$v_{max} \sim 1/\sin\alpha \qquad (2)$$

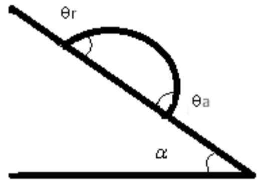

Figure 6 Schema of drop in tilt surface

Therefore, high angles result in low volume/small drops being the first to slip off the substrate. Results presented in Figure 7 shows the influence of the angle of inclination α as a function of time $t_{\downarrow}$. As expected, it is observed that, the more important is the angle of inclination, the earlier droplets detach. A variation proportional to $1/sin\alpha$ is obtained, consistent with equation (2). (The run-off time shorter at 75° than at 90° is due to measurement uncertainties).

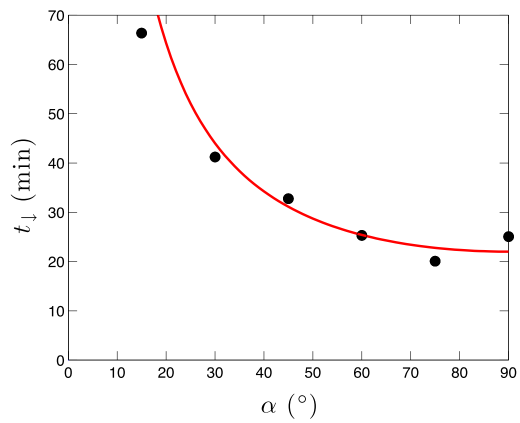

Figure 7 Start of run-off time as function of tilt angle α for s = w = h = 65 µm, RH = 50%, T = 33°C, T_P = 6°C.

Influence of geometrical parameters

We consider here the stage of the condensation process where droplets are large enough to slide down to the bottom of the plate in order to be collected. Just before shedding, a drop has a shape similar to the image in Figure 8. It covers several grooves and its volume is around a few mm^3.

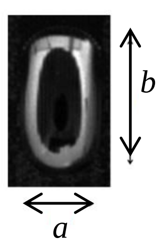

Figure 8 Picture of the droplet of width a and length b.

Figures 9 and 10 show the influence of depth h on the start of run-off and on the shape and size of the drops, for s = 65 µm and w = 100 µm. For values of h between 40 and 150 µm, the run-off start time (Figure 9) and the size and shape of the drops (Figure 8) shows very little variations with h. Then the pinning force is independent of h. This independency can be explained by the fact that the pinning forces, located on the triple vapor-liquid-solid line on the groove plateau, does not depend on the h height of liquid in the grooves.

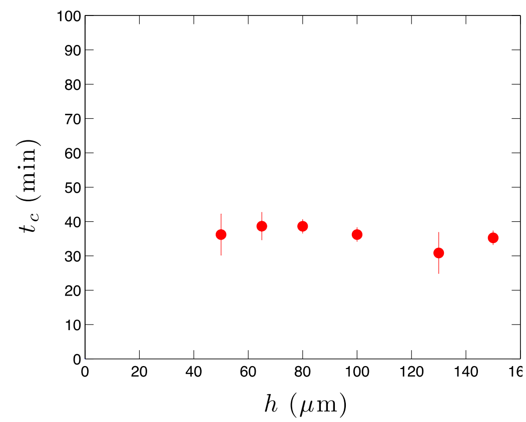

Figure 9 Run-off start time as a function of height h for s = w = 65 µm, α = 30°, RH = 50%, T = 33°C, T_P = 5°C.

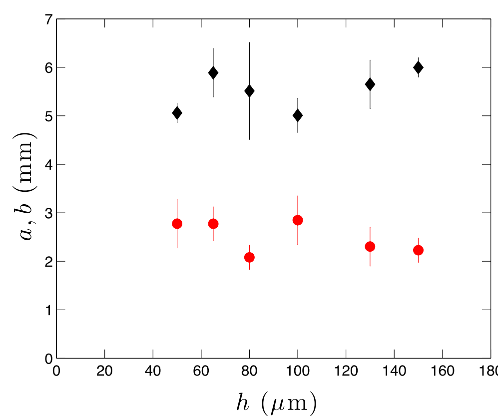

Figure 10 Geometric parameters of the drop as function of height h for s = w = 65 µm, α = 30°, RH = 50%, T = 33°C, T_P = 5°C.

Figure 11 shows the influence of the groove width s on the run-off start time for h = 65 m and w = 100 m. The droplet coalescence process on the top of grooves is increased when the values of s becomes low (50 µm < s < 150 µm) as compared with the results obtained for large value of s (=300 µm). For high values of s, the channel does not fill completely with water and the process becomes comparable to what is observed with a smooth surface.

Figure 12 shows the influence of groove width w on the run-off start time for h = 65 µm and s = 100 µm. One can observe that more thinner is the groove width, more quick begins drop harvesting. For w <100 µm, the drops begin to shed after 20 min, while it takes more than one hour when w> 300 microns. This result is explained by a decrease of the pinning forces of the triple vapor-liquid-solid line on the groove plateau. The drops become more and more elongated (Figure 11) for w <150 µm as a result of that decrease.

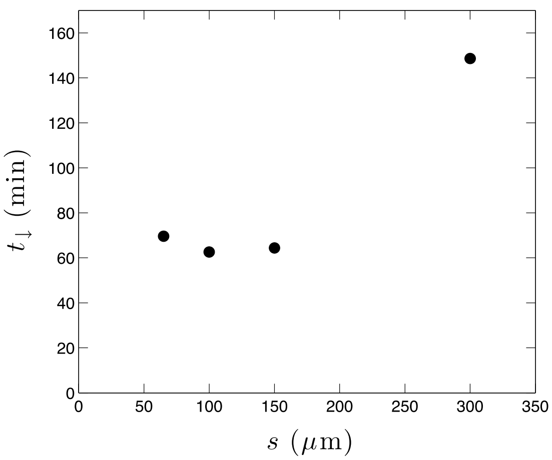

Figure 11 Run-off start time as a function of groove channel width s for w = 100 µm, h = 65 µm, α = 30°, RH = 40%, T = 33°C, T_P = 3°C.

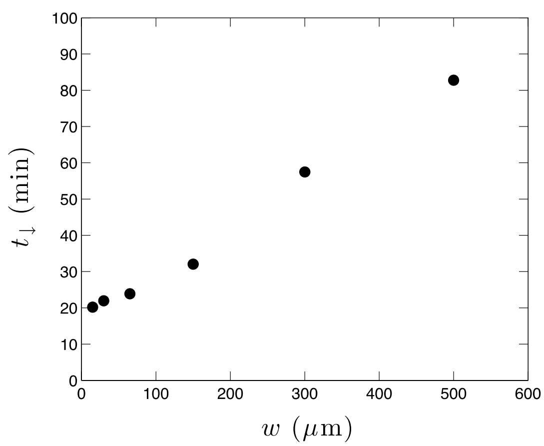

Figure 12 Run-off start time as a function of groove plateau width w for s = 100 µm, h = 65 µm, α = 45°, RH = 50%, T = 33°C, T_P = 12°C.

CONCLUSIONS

This comparative study of atmospheric water vapor condensation on grooves and smooth surfaces shows that grooves increase coalescence between drops and also reduce pinning forces. Drops then reach sooner the critical size to shed than on smooth surfaces with same wetting properties and greater amount of water is collected. The most suitable geometrical parameters to promote drop coalescence are found in a range lower than 150 µm. In that range, the height of the grooves has no influence on the run-off start time.

Harvesting natural dew on passive condensers can then be much improved by using grooves. The factor depends on the actual condensation rate and condensation time. However, it is anticipated at least a factor 2 increase (high condensation rate and long condensation time as in the present experiment) and much more for low condensation rates and small condensation times, where dew water can be hardly collected by smooth surfaces. In order to go further and try to improve the condenser yield, tuning the wetting properties by grafting polymers will be considered in a next future.

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