

RESEARCH ARTICLE

Comparison of condensation rates of surfaces mimicking the desert toktokkie beetle spot pattern and leaf vein skeleton pattern

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Abstract - This paper presents an investigation of condensation rate on surfaces with hydrophilic and hydrophobic patterns, inspired by the desert toktokkie beetle spot pattern and the leaf vein skeleton pattern. The objective of this paper is to compare the condensation rate of surfaces inspired by the desert toktokkie beetle spot pattern and the leaf vein skeleton pattern. Five types of surfaces, which were the desert toktokkie beetle spot pattern, leaf vein skeleton pattern, untreated copper, PVC-coated, and laser-etched surfaces, were prepared. The measured contact angles of a water droplet on the untreated copper, PVC-coated, and laser-etched surfaces were 62.21°, 101.99°, and 54.75°, respectively. The condensation rates of water vapour on the five surface types were subsequently measured through experiments. The heat released from condensation was measured using a thermoelectric module. The rate of cooling power of the thermoelectric module is proportional to the condensation rate. The condensation rate of the surface with the desert toktokkie beetle spot pattern is 22.9% higher than that of the untreated copper surface. However, the condensation rate of the surface with the leaf vein skeleton pattern is only 9.53% higher than that of the untreated copper surface. The desert toktokkie beetle spot pattern induces the coalescence of droplets, which enhances the removal of condensate from the surface. The desert toktokkie beetle spot pattern also reduces the fluctuations in condensation rate by half, compared to the untreated copper surface. With appropriate adoption of features from nature, there is potential to reduce the size of a condenser.

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1. Introduction

Efficient condensation is one of the aims in the design of many engineering devices. For instance, efficient condensation can reduce the size of a condenser, enabling the design of compact condensers that require less space for installation and less material for fabrication. In the condenser of refrigeration systems, microchannels are widely adopted to reduce its size [1]. Microchannels significantly enhance the performance of vapour compression refrigeration systems [2]. Similar technology is also relevant to the condensers in heating, ventilating, and air conditioning systems [3]. For other geometries where the microchannel is not applicable, the imitation of nature is one of the approaches that can be adopted in developing a more efficient condenser. Thus, the objective of this paper is to compare the condensation rate of modified surfaces inspired by the desert toktokkie beetle spot pattern and leaf vein skeleton pattern.

Condensation of vapour on a surface generally occurs in two modes, which are dropwise or filmwise condensation. Dropwise condensation is preferred because it provides significantly higher heat transfer coefficients than filmwise condensation, as the condensate droplets are continuously removed, exposing the condenser surface to incoming vapour [4]. However, many engineering surfaces cannot sustain dropwise condensation over extended periods because the droplets eventually coalesce into a continuous liquid film [5]. Consequently, surface modification is required to promote and maintain dropwise condensation.

Surface modification involves physical or chemical alterations. The purpose of surface modification is to control the condensate behaviour during the nucleation, growth, coalescence, and transport of condensate droplets, thereby enhancing condensation heat transfer [6]. As a result, many researchers have focused on developing surface modification techniques that promote stable dropwise condensation and improve the thermal performance of condensers.

The combination of hydrophobic and hydrophilic surfaces balances condenser and evaporator performance [7]. This indicates that the rate of condensation is controllable by surface manipulation. By varying wettability, hydrophilic, neutral, and hydrophobic serrated periodic triangular surfaces, the condensation rate can be increased [8]. However, these approaches involve complex surface modification, which can lead to high manufacturing costs. Another effort to increase the condensation rate by applying a vertical pattern of hydrophobic and hydrophilic surfaces has been reported [9]. This vertical pattern was not inspired by any features from living organisms. There is an ongoing argument regarding the optimal contact angle, as a hydrophobic surface does not always enhance the condensation rate [10]. However, this hypothesis has not yet been investigated in the context of nature-inspired surface designs. To promote droplet coalescence, electrowetting can be employed [11]. These studies [10], [11] have evaluated hydrophobic and hydrophilic surfaces separately, without incorporating nature-inspired principles into the design.

In nature, the methods of condensation rate enhancement are drop jumping, sweeping, and superwetting [12], or it can be a combination of droplet coalescence-induced jumping [13]. These methods can be mimicked to enhance the condensation rate in condensers. In research related to bioinspired condensation surfaces, the Desert Beetle Elytra structure was fabricated using aluminium [14]. The fabrication of superhydrophilic surfaces involves a laborious chemical

process. This may lead to higher manufacturing costs. Research on micro-scale and dual-scale roughness is also reported [15]. Similarly, the fabrication process of the surface is associated with significant technical challenges. The performance of surfaces with protruded designs inspired by the Namib desert beetle, dune Bushman grass, and rice leaves dedicated to condensation in arid regions is reported [16]. The protruded structure adopted in this research may not be necessary for condensation. Therefore, we argue that biomimetic surfaces do not require protruding surface structures to enhance the condensation rate, reducing complexity in surface modification.

Our work concerns the condensation rate of biomimetic surfaces inspired by the desert toktokkie beetle (*Physasteria cribripes*) and leaf vein skeleton. Our justifications for selecting the desert toktokkie beetle spot pattern and leaf vein skeleton pattern are given here. The desert toktokkie beetle possesses specialised structures on their exoskeleton that have a combination of hydrophilic and hydrophobic surfaces [17]. During early morning and when fog blankets the desert, the beetle assumes a headstanding position, lifting its abdomen into the fog-laden breeze. As water vapor in the air makes contact with the beetle's body, the hydrophilic surfaces promote condensation into droplets, which are then guided to its mouth by hydrophobic valleys once they reach a critical size [18]. For the leaf vein skeleton pattern, the shape of the vein may provide the drainage mechanism for condensate that could increase the rate of droplet removal, as reported in [16]. Other bio-inspired designs for collecting moisture, such as spider silk, are reported elsewhere [19]; however, they are beyond the scope of our research.

The objective of this paper is to compare the condensation rate of modified surfaces inspired by the desert toktokkie beetle spot pattern and leaf vein skeleton pattern. To achieve our objective, surfaces with hydrophilic and hydrophobic patterns inspired by the desert toktokkie beetle spot pattern and leaf vein skeleton pattern were fabricated. Then, the condensation rates of water vapour on these surfaces were measured in experiments. Finally, the mechanisms of condensation for these two surfaces were discussed.

2. Materials and Methods

This section begins with the preparation of samples for condensation rate experiments and the procedure to measure the contact angle of water droplets on their surfaces. Then, the apparatus and procedure to measure the condensation rate of the prepared samples, and data analysis are elaborated.

2.1 Preparation of samples and contact angle measurement

2.1.1 Preparation of samples for condensation rate measurement

In this study, five different samples with different surface conditions were prepared, as listed in Table 1. All specimens used 3 mm-thick Grade C11000 high-purity copper as their base. Each specimen had a surface area of 50 mm × 50 mm for condensation. The untreated copper surface served as the baseline for evaluating the condensation rate. A PVC-coated surface and a laser-etched surface were prepared as reference surfaces representing hydrophobic and hydrophilic conditions, respectively. The thickness of the PVC film used for coating is 0.13 mm.

The desert toktokkie beetle spot pattern and the leaf vein skeleton pattern were fabricated using a two-step process: (1) laser etching at the designated positions, and (2) coating the remaining non-etched regions with a PVC film and water-repellent solution. The dimensions of the laser-etched and PVC-coated regions for the desert toktokkie beetle spot pattern and the leaf vein skeleton pattern are presented in Figures 1 and 2, respectively.

Table 1. Name of sample and its surface treatment

Name of sample	Type of surface modification
Untreated	No modification
PVC-coated	0.13 mm PVC film coating and water-repellent solution
Laser etched	Laser etching
Desert toktokkie beetle spot pattern	Laser etching, 0.13 mm PVC film coating, and water-repellent solution
Leaf vein skeleton pattern	

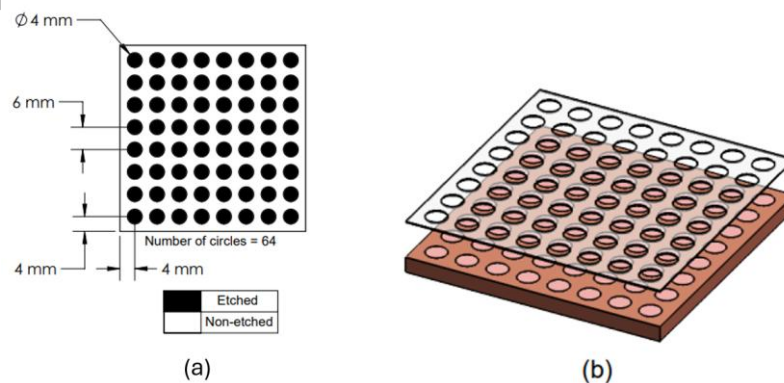


Figure 1. The geometry of the etched surface and PVC film for the desert toktokkie beetle spot pattern sample

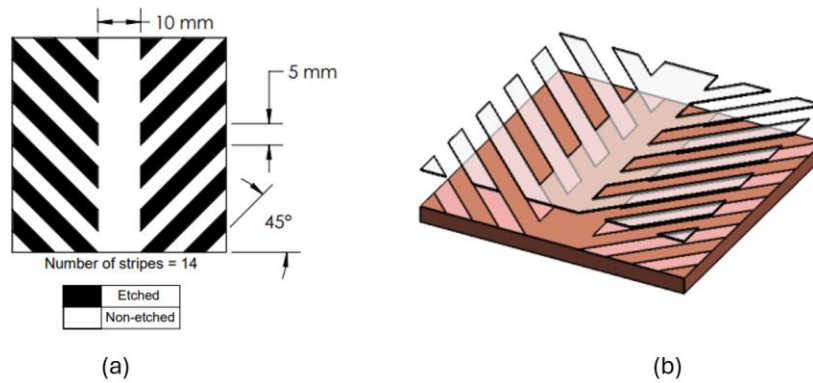


Figure 2. The geometry of the etched surface and PVC film for the leaf vein skeleton pattern sample

2.1.2 Measurement of contact angle

The untreated, laser-etched, and PVC-coated samples fabricated in Section 2.1.1 were used for contact angle measurements of a water droplet to evaluate their surface wettability. The objective of this measurement was to determine whether each surface exhibited hydrophilic or hydrophobic characteristics.

Each sample was placed on a horizontal surface, and a 0.2 mL droplet of distilled water was carefully dispensed onto the surface using a syringe. A side-view image of the droplet was then captured, as shown in Figure 3(a). The captured image was analysed using ImageJ software, where the droplet profile was fitted using 14 equally spaced control points (blue knots). The contact angle was subsequently determined by measuring the angle between the tangent to the fitted droplet profile at the liquid surface and the sample surface, as illustrated in Figure 3(b). The measurements were made after the changes in contact angles became negligible (i.e., the standard deviation of the contact angle was less than 0.7°).

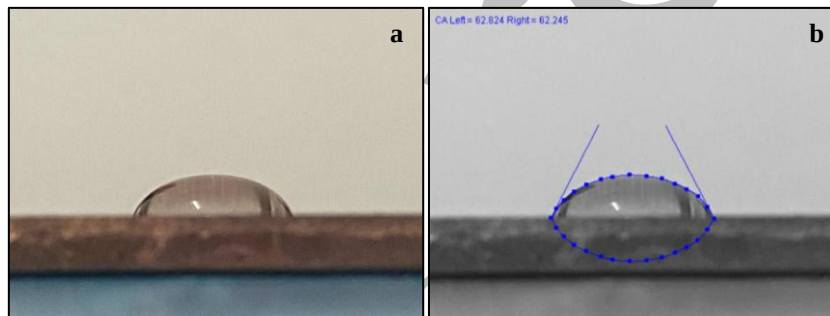


Figure 3. Measurement of the contact angle of a water droplet on an untreated copper surface: a) Formation of a water droplet on the surface, and b) contact angle measurement between the tangent to the fitted droplet profile at the liquid and the sample surface

2.2 Measurement of condensation rate

2.2.1 Apparatus

The arrangement of the experimental apparatus is shown in Figure 4. It consists of a water vapour generator, a sample, a thermoelectric module, a heat sink, a DC axial fan, an acrylic panel enclosure, and K-type thermocouples (TC_{vapour} , TC_C , and TC_H) with a PicoLog TC-08 thermocouple data logger. The water vapour generator (Model EF-501), with a rated power of 400 Watt was used to produce steam. The steam was confined inside the acrylic panel enclosure. The influence of ambient conditions on the steam is negligible.

The sample that was prepared in Section 2.1.1 was placed onto the surface of a thermoelectric module (Model TEC1-12706) so that the heat from condensation could be dissipated from the sample. The other surface of the thermoelectric module is in contact with a heat sink and a DC axial fan. The heat sink and DC axial fan are located outside the acrylic enclosure. The dimensions of the thermoelectric module are 40 mm x 40 mm with 4 mm thickness. The module's rated voltage and current of the module are 12 V and 6 Ampere, respectively. The aluminium heat sink has the dimensions of 90 mm x 90 mm x 4 mm at its base. It has 14 fins with the dimensions of 90 mm x 36 mm x 4 mm. The DC axial fan (Model GH9225M12S) has dimensions of 92 mm x 92 mm x 25 mm and maximum rated voltage and current of 12 V and 0.18 A, respectively.

The thermocouple at position TC_{vapour} measured the temperature of vapour near the surface of the sample. The thermocouple TC_C measured the cold surface temperature (T_C) of the thermoelectric module. The thermocouple TC_H measured the hot surface temperature (T_H) of the thermoelectric module.

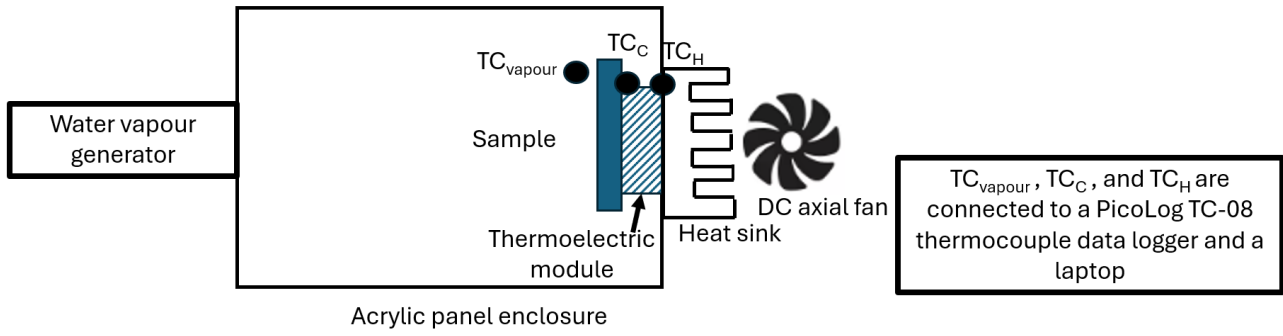


Figure 4. Schematic diagram of the experimental apparatus for condensation rate measurements

2.2.2 Experimental procedure

Throughout the experiment, the voltage supply to the thermoelectric module was kept constant at 12 V, and the current was between 2.5 and 2.6 Ampere. The DC axial fan was supplied with 12 V DC to ensure it was operating at a constant speed throughout the experiment. Each experiment took 50 minutes. To achieve a fairly constant heat flow through the thermoelectric module, the thermoelectric module and DC axial fan were run for 10 minutes (0th minute to 10th minute).

Then, the water vapour generator was switched on to release vapour for 30 minutes (10th minute to 40th minute). Then, the experiment was continued from the 40th minute to the 50th minute, with the water vapour generator turned off. At every minute, the electrical current and temperatures were recorded. The temperature of the vapour near the surface of the sample was at $85^{\circ}\text{C} \pm 10^{\circ}\text{C}$ throughout the experiment.

2.2.3 Data and error analysis

The condensation rate was inferred from the cooling power of the thermoelectric module. The magnitude of cooling power (Q_A) on the cold surface of the thermoelectric module was calculated using Equation 1:

$$Q_A = \alpha IT_C - \frac{1}{2} I^2 R - k(T_H - T_C) \quad (1)$$

where Q_A is the cooling power produced by the thermoelectric module (W), α is the Seebeck coefficient, taken as 0.0543 V/K, I is the electrical current; R is the electrical resistance, taken as 1.98Ω if the average temperature of the hot and cold sides of the module is 25°C , and 2.30Ω for 50°C [20]. In between, the resistance was linearly interpolated. The k is the module thermal conductivity, taken as 0.5473 W/K, T_H is the module hot surface temperature, and T_C is the module cold surface temperature. Further information for the equation is available in [21]. Throughout the experiments, the average temperature of the surfaces of the thermoelectric module is between 25°C and 50°C .

The sources of uncertainty that can affect the comparison of condensation rates between samples are: (1) 0.8 % due to the variation in vapour temperature (ΔQ_{vapour}), and (2) 3% due to the linear interpolation of the module's electrical resistance, and uncertainties in electrical current and temperature measurements (ΔQ_A). The total uncertainty of the cooling power ($\Delta Q_{A,total}$) is estimated at 3.1%.

The derivation and equations used for the quantification of uncertainties (i.e., ΔQ_{vapour} and ΔQ_A) are available in Equations 2 through 5. In Equation 2, $C_{p,vapour}$ is the specific heat of water vapour, and h_{fg} is the latent heat of water. The possible values of cooling power (i.e., maximum ($Q_{A,max}$) and minimum ($Q_{A,min}$)) were calculated using Equation 3 and Equation 4, respectively. Then, the greatest uncertainty was taken from the absolute difference (ΔQ_A) between $Q_{A,max}$ or $Q_{A,min}$ and Q_A , calculated using Equation 5. Then, the total uncertainty ($\Delta Q_{A,total}$) was calculated using Equation 6.

$$\Delta Q_{vapour} = ((C_{p,vapour} \times \Delta T_{vapour}) / h_{fg}) \times 100\% \quad (2)$$

$$Q_{A,max} = \alpha(I + \Delta I)(T_C + \Delta T_C) - \frac{1}{2}(I + \Delta I)^2(R + \Delta R) - k((T_H + \Delta T_H) - (T_C + \Delta T_C)) \quad (3)$$

$$Q_{A,min} = \alpha(I - \Delta I)(T_C - \Delta T_C) - \frac{1}{2}(I - \Delta I)^2(R - \Delta R) - k((T_H - \Delta T_H) - (T_C - \Delta T_C)) \quad (4)$$

$$\Delta Q_A = \max(\text{abs}((Q_{A,max} - Q_A)/Q_A), ((Q_{A,min} - Q_A)/Q_A)) \times 100\% \quad (5)$$

$$\Delta Q_{A,total} = \sqrt{(\Delta Q_{vapour})^2 + (\Delta Q_A)^2} \quad (6)$$

Table 2. Uncertainty analysis

Source of uncertainty	Uncertainty, Δ	Quantification of uncertainties	Worst uncertainty
<i>Variation in water vapour temperature</i>			
Water vapour temperature (T_{vapour})	$\pm 10^\circ\text{C}$	Equation 2	0.8%
<i>Cooling power measurement by thermoelectric module</i>			
Electrical resistance (R)	0.0128 ohm/K	Equation 3, Equation 4, and Equation 5	3%
Electrical current (I)	± 0.05 Ampere		
Cold surface temperature (T_C)	$\pm 0.5^\circ\text{C}$		
Hot surface temperature (T_H)	$\pm 0.5^\circ\text{C}$		

3. Results and Discussion

This section presents the measured contact angles of a water droplet on the untreated, PVC-coated, and laser-etched surfaces. Then, the characteristics of condensate and condensation rate for the untreated, PVC-coated, laser-etched, desert toktokkie beetle spot pattern, and leaf vein skeleton pattern are presented and discussed.

3.1 Contact angle of water droplet

The purpose of contact angle measurement is to determine the hydrophobicity and hydrophilicity of the surfaces. This is essential to ensure that the modified surfaces possess the intended patterns of hydrophobicity and hydrophilicity. Thus, the measurements were made for untreated, PVC-coated, and laser-etched surfaces. It is worth noting that these surfaces have no patterns, to eliminate the influence of the pattern on the contact angle.

The images of contact angle measurements for the untreated, PVC-coated, and laser-etched surfaces are presented in Figure 5. To reduce the measurement uncertainties, the experiment was repeated three times. The average contact angles for the untreated, PVC-coated, and laser-etched surfaces were 62.21° , 101.99° , and 54.75° , respectively. According to [6], a contact angle greater than 90° indicates a hydrophobic surface, while a contact angle less than 90° indicates a hydrophilic surface. Based on the measured contact angles, it can be concluded that the untreated and laser-etched surfaces are hydrophilic. The laser-etched treatment on the copper surface increases its level of hydrophilicity, indicated by the reduction in contact angle by 7.46° . The contact angle for the laser-etched copper surface is within the range of the value reported in [22]. The PVC-coated surface is hydrophobic, with a contact angle that is 11.99° higher than the threshold for a hydrophobic surface. The measured contact angle for the PVC-coated surface is comparable to the value reported in [23].

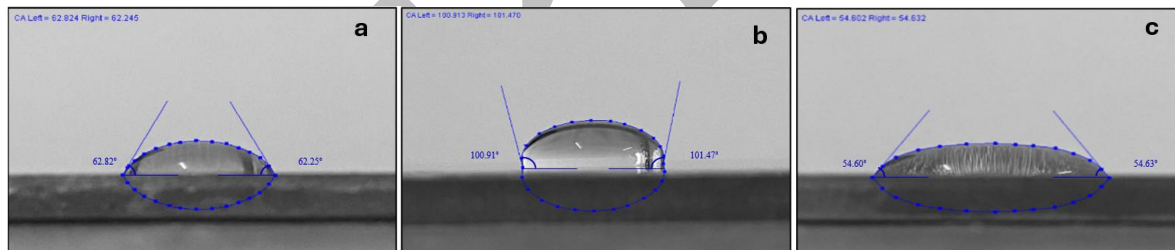


Figure 5: Contact angle measurement of a water droplet on (a) untreated, (b) PVC-coated, and (c) laser-etched surfaces

3.2 Characteristics of condensate on the surfaces

Figure 6 shows the formation of condensate on the untreated, PVC-coated, laser-etched, desert toktokkie beetle spot pattern, and leaf vein skeleton pattern surfaces. The pictures were taken at the end of each experiment. In general, the sizes of the droplets on the hydrophobic surfaces are larger than the droplets on hydrophilic surfaces. In Figure 6(a), the droplets are clearly visible on the untreated surface. The sizes of the droplets on the untreated surface are larger than on the PVC-coated surface, as in Figure 6(b). This indicates that the hydrophobic properties of the PVC-coated surface reduce the size of the droplets. For the laser-etched surface as shown in Figure 6(c), the formation of water droplets is less visible compared to the untreated and PVC-coated surfaces. A thin layer of water may be trapped within the uneven profiles of the laser-etched surface.

In Figure 6(d), the density of water droplets on the desert toktokkie beetle spot pattern is higher compared to other surfaces. The characteristics of droplet formation in Figure 6(d) can be further classified into the upper region (dashed box 1) and the bottom region (dashed box 2), as in Figure 7(a). In dashed box 1 of Figure 7(a), larger water droplets are formed within the circular laser-etched region. The circumference of this circular laser-etched region is surrounded by smaller water droplets. In dashed box 2, there are more water droplets accumulated at the bottom of the surface compared to other samples. There is evidence of coalescence of water droplets between the hydrophilic and hydrophobic regions. This may increase the rate of droplet removal and make more nucleation sites available for the formation of the next droplet. Similar observations were reported in [24] for a staggered hydrophobic pattern.

For the leaf vein skeleton pattern sample as shown in Figure 6(e), there is a difference in density of droplet formation in the hydrophilic and hydrophobic regions. A closer observation of the droplet pattern can be categorised into three regions as detailed in Figure 7(b). The dashed box 1 has the highest density of droplet formation. The coalescence of droplets between the hydrophobic and hydrophilic surface are evidenced. However, the size of the droplets is not

significantly larger. In dashed box 2, similar droplet patterns to the PVC-coated temperature can be observed. In dashed box 3, the density of droplets in the bottom region is less than that of the desert toktokkie beetle spot pattern sample.



Figure 6: Condensate formation on (a) Untreated (b) PVC-coated (c) laser etched (d) desert toktokkie beetle spot pattern, and (e) leaf vein skeleton pattern samples

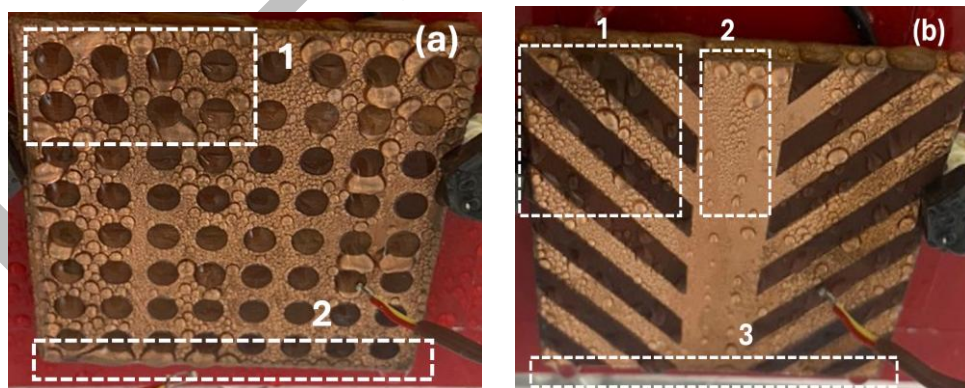


Figure 7: Condensate formation on (a) desert toktokkie beetle spot pattern, and (b) the leaf vein skeleton pattern samples

3.3 Rate of condensation

Figure 8 shows the comparison of cooling power produced by the thermoelectric module for the untreated, PVC-coated, laser-etched, desert toktokkie beetle spot pattern, and leaf vein skeleton pattern samples. The estimated uncertainty in cooling power of the thermoelectric module is 3.1%, which makes the comparison of condensation rates between samples valid.

In general, the desert toktokkie beetle spot pattern has the highest cooling power, as shown in Table 3. This can be explained by a higher density of droplets compared to other samples, as reported in Section 3.2. The desert toktokkie beetle spot pattern sample has a condensation rate that is 23% higher than the untreated surface. The untreated sample has the lowest cooling power. This means that it is necessary to modify the surface to increase its condensation rate.

Another observation is on the consistency of the cooling power. The desert toktokkie beetle spot pattern sample has the lowest standard deviation in its thermoelectric cooling power, while the coated and etched samples have higher standard deviations. A higher standard deviation indicates inconsistency in the rate of condensation. This proves that the desert toktokkie beetle spot pattern is superior, with a relatively higher condensation rate and better consistency in the condensation rate.

Table 3. The average and standard deviation of the cooling power produced by the thermoelectric module

Name of sample	Average cooling power (W)	Standard deviation of cooling power (W)	Percentage of increase compared to the untreated surface (%)
Untreated	14.61	0.58	Baseline
PVC-coated	15.88	1.96	8.73
Laser etched	15.54	1.94	6.39
Desert toktokkie beetle spot pattern	17.96	0.31	22.94
Leaf vein skeleton pattern	16.00	0.53	9.53

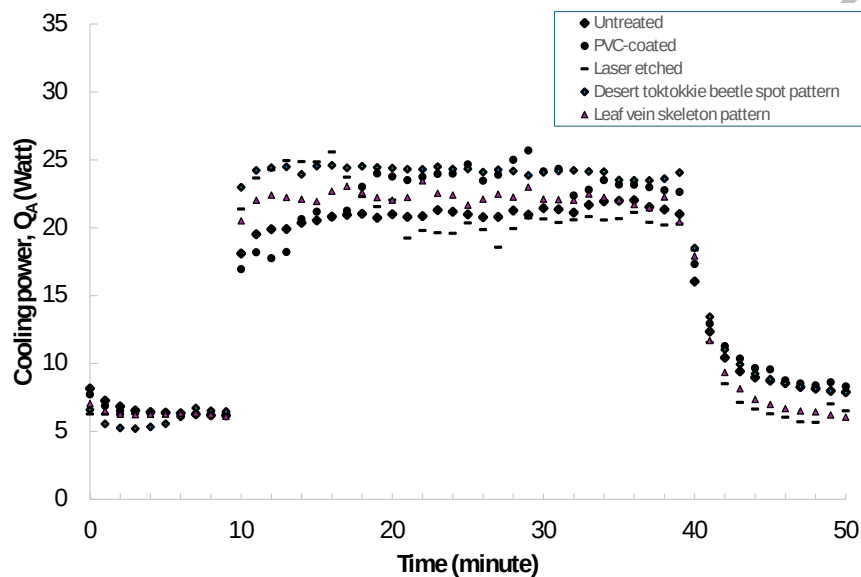


Figure 8: The cooling power of the thermoelectric module for the five samples

3.4 Discussion

The findings of this study indicate that modifying the surface to be either hydrophobic or hydrophilic alone is insufficient to significantly enhance the condensation rate. This statement is supported by the relatively small differences in condensation rates between the coated or laser-etched surfaces and the untreated surface, which were less than 9%, as can be observed in Table 3. In contrast, incorporating both hydrophobic and hydrophilic regions in a patterned surface improved the condensation rate, most likely by promoting more efficient condensate transport across the copper surface. However, the design of the hydrophobic–hydrophilic pattern requires further optimisation. For example, the leaf vein skeleton pattern surface achieved a condensation rate that was less than 3% higher than that of the uniformly etched or coated surfaces. Such a modest improvement may not justify the additional complexity and cost incurred by surface modification. Therefore, the selection of an appropriate surface pattern should be carefully evaluated through both technical and economic analyses. This may explain why the beetle spot pattern is frequently adopted [25]. Otherwise, the additional cost of surface preparation may outweigh the benefits, making the overall reduction in fabrication costs difficult to justify.

The fluctuations in cooling power indicate that the condensation process is unsteady. In engineering applications, a stable condensation rate is generally preferred because it minimises fluctuations in thermal stresses within the condenser. These fluctuations may also suggest that condensate is distributed less uniformly across the condenser surface. The fluctuations were less pronounced for the leaf vein skeleton pattern, desert toktokkie beetle spot pattern, and untreated samples. This observation suggests that the PVC-coated and laser etched samples promote a more unsteady and potentially less uniform condensation process than the patterned surfaces. The results further indicate that incorporating hydrophobic–hydrophilic patterns on the copper surface not only enhances the condensation rate but also improves the stability and uniformity of the condensation process. A more uniform condensation process may simplify heat exchanger design by reducing localised thermal gradients and improving the predictability of condenser performance. Consequently, thermal performance models may provide more accurate predictions under steady operating conditions.

It is generally accepted that fully replicating natural surfaces is neither technically nor economically feasible. For example, the surface of the desert toktokkie beetle is not flat but consists of complex and irregular hydrophobic and hydrophilic regions. A comprehensive understanding of this surface would require a holistic investigation under

environmental conditions that closely replicate those of its natural desert habitat. Furthermore, the surface properties of the desert toktokkie beetle may adapt dynamically to variations in moisture, temperature, and the beetle's physiological requirements for water collection. Such adaptive characteristics involve complex interactions that are currently beyond the capabilities of existing manufacturing technologies, materials science, and control engineering. To overcome these challenges, a simplified surface design inspired by the toktokkie beetle spot pattern can be adopted. Although such a design does not fully replicate the biological structure, it enables the investigation of the key mechanisms responsible for enhanced condensation while maintaining its practicality for engineering applications and large-scale manufacturing.

The experimental method presented in this study can be further improved by increasing the cooling capacity of the thermoelectric module. A higher cooling capacity would ensure that the condensation rate is not constrained by the module, particularly when evaluating surfaces that promote enhanced condensation. In the present study, however, the cooling capacity of the thermoelectric module did not appear to limit the condensation process. This is demonstrated by its ability to maintain a stable condensation rate for the desert toktokkie beetle spot pattern sample, which exhibited the lowest fluctuation in cooling power among all the tested surfaces. Another limitation of the current experimental setup is that it is designed to evaluate only flat surfaces. Since many engineering components incorporate curved or complex geometries, future studies should consider developing an experimental apparatus capable of accurately measuring condensation rate on non-flat surfaces. Such an improvement would broaden the applicability of the experimental method to practical engineering systems.

4. Conclusions

This research aims to investigate the relative condensation rates of five different surfaces. Two of the surfaces were inspired by the desert toktokkie beetle spot pattern and leaf vein skeleton pattern. The experimental results show that the surface with the desert toktokkie beetle spot pattern had the highest condensation rate, 22.9% higher than the untreated surface. The condensation rate of the surface with the leaf vein skeleton pattern is 9.53% higher than the untreated surface. The rate of condensation for the leaf vein skeleton pattern sample is comparable to the laser etched and PVC-coated samples, which were between 6 and 9 percent higher than the untreated sample. The steadiness of the condensation rate for the desert toktokkie beetle spot pattern sample is at least two times better than other samples. These findings demonstrate that incorporating natural design principles into engineering devices can contribute to improvement in condensation performance. However, a proper approach is needed because, as found in this research, the leaf vein skeleton pattern sample did not show a remarkable improvement compared to the untreated copper surface sample. Since the surface modification in this work has much less complexity compared to other reported research, the adoption of the findings into commercial engineering devices will be relatively less costly.

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Declaration of Competing Interests

The authors declare no conflicts of interest.

CRediT Author Contribution Statement

Mohamad Asmidzam Ahamat: Conceptualisation; Supervision; Formal Analysis; Writing - Review and Editing.

Muhammad Hazman Saafie: Methodology; Investigation; Formal Analysis; Writing - Original Draft.

Availability of Data and Materials

- **Available on request:** The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement

Not applicable since this research did not involve human participants, animals, or sensitive personal data.

Generative Artificial Intelligence Disclosure

Language editing only: AI-based tools were used solely for language editing and grammar refinement. No AI content generation or data interpretation was performed. All intellectual contributions are original and solely attributable to the authors.

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