Check for updates

RESEARCH ARTICLE

Investigation of the effects surface alteration via coatings on the condensation heat transfer and wettability

[version 1; peer review: 3 approved with reservations]

David F Martelo[1], Georgia Schneider[1], Imran Bhamji[1], Anna Wojdyla[1], Garima Mittal[2], Nigar Gul Malik[2], Arunima Bhuvanendran Nair Jayakumari[2], Namrata Kale[1], David Ingvi Snorrason[3], Arni Ingason[3], Paolo Taddei[4], Shiladitya Paul[1,2]

[1]The Welding Institute, Cambridge, England, CB21 6AL, UK
[2]Materials Innovation Centre, School of Engineering, University of Leicester, Leicester, England, LE1 7RH, UK
[3]Grein Research, Reykjavik, Iceland
[4]Spike Renewables, Firenze, Italy

v1 **First published:** 12 Jan 2024, **4**:20
https://doi.org/10.12688/openreseurope.16802.1
Latest published: 12 Jan 2024, **4**:20
https://doi.org/10.12688/openreseurope.16802.1

Abstract

Background

Heat exchangers are a critical component in organic Rankine cyclic (ORC) geothermal power plants as they represent more than 50% of the capital. In this study, the thermal performance of coatings devised for condensation heat exchangers have been studied.

Methods

For this purpose, a mock-up heat exchanger rig was designed and fabricated. The coatings used for the trials are of hydrophobic nature, in order to promote a change in the heat transfer mode from film-wise condensation to drop-wise condensation. The coatings for this study were developed by chemical vapour deposition and magnetron sputtering on aluminium substrates. The wettability and adhesion of the coatings was characterized before and after the tests. Statistical analysis was used to analyse the heat transfer related data.

Results

The results indicate that the silica based coating produced an improvement in the heat transfer performance indicators and the working fluid caused a deterioration of the wetting properties.

Open Peer Review

Approval Status ? ? ?

	1	2	3
version 1 12 Jan 2024	? view	? view	? view

1. **Mete Budakli**, Ozyegin University, Istanbul, Turkey
2. **AM Kamalan Kirubaharan**, Alexander Dubck University of Trencin, Slovakia, Trencin, Slovakia
3. **Soumyadip Sett**, Indian Institute of Technology Gandhinagar, Palaj, India

Any reports and responses or comments on the article can be found at the end of the article.

However, even at the end of the tests, the coated samples performed better than the substrate material in terms of heat transfer performance.

Conclusions

The results of this research prove that shifting from film-wise condensation to drop-wise condensation is viable method to improve heat transfer efficacy. However, a one to one correlation could not be established with water contact angles measured in water or diiodomethane suggesting that wettability properties in ORC fluid could differ to established in these conventional fluids for contact angle measurements.

Plain language summary
Geothermal is a type of renewable energy that uses the heat within the earth. One of the main drawbacks of this source of energy is the high capital cost. Among the most important and costly equipment in a geothermal plant is the heat exchanger. The implementation of coatings can assist in the increasing the performance and reduce the cost in the heat exchangers. This investigation focused on the development of novel coatings for condensation heat exchangers. These are a type of heat exchangers that are normally located after the turbine in a geothermal plant, and the improvement in its performance can be achieved by a more efficient conversion of the vapour to liquid phase of working fluid. The coatings investigated in this research are of different variety; moreover, the improvement in performance is given by changing the wettability of the working fluid on the surfaces where heat exchange takes place. The results of this research are very promising, and in the next step of this project, the coatings will be implemented in commercial heat exchangers.

Keywords
dropwise condensation, hydrophobic coatings, heat transfer performance

This article is included in the Horizon 2020 gateway.

This article is included in the Electrical, Electronic and Information Engineering gateway.

Corresponding authors: David F Martelo (david.martelo@twi.co.uk), Shiladitya Paul (shiladitya.paul@twi.co.uk)

Author roles: Martelo DF: Conceptualization, Investigation, Methodology, Project Administration, Writing – Original Draft Preparation; **Schneider G**: Formal Analysis, Writing – Original Draft Preparation; **Bhamji I**: Conceptualization, Methodology, Project Administration; **Wojdyla A**: Investigation; **Mittal G**: Investigation; **Malik NG**: Investigation, Writing – Original Draft Preparation; **Nair Jayakumari AB**: Investigation; **Kale N**: Conceptualization, Project Administration; **Snorrason DI**: Investigation; **Ingason A**: Investigation; **Taddei P**: Resources; **Paul S**: Conceptualization, Methodology, Supervision, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This work is a part of the H2020 EU project GeoHex: "Advanced material for cost-efficient and enhanced heat exchange performance for geothermal application" funded by European Union (Grant agreement no.- 851917). The authors would also like to acknowledge the collaborative efforts of all partners in the GeoHex project.
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Copyright: © 2024 Martelo DF *et al*. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

How to cite this article: Martelo DF, Schneider G, Bhamji I *et al.* **Investigation of the effects surface alteration via coatings on the condensation heat transfer and wettability [version 1; peer review: 3 approved with reservations]** Open Research Europe 2024, **4**:20 https://doi.org/10.12688/openreseurope.16802.1

First published: 12 Jan 2024, **4**:20 https://doi.org/10.12688/openreseurope.16802.1

Introduction

Efficient heat transfer has always been a subject of considerable interest and is essential for enhancement of a system's overall performance, energy efficacy, and to minimize operational costs[1]. Phase change heat transfer holds paramount importance in energy-related fields owing to its substantial amplification of heat transfer due to the difference between latent and sensible heat[2]. Heat transfer enhancement techniques are categorized into two methods; active and passive techniques[1]. Active techniques rely on mechanical or electrical energy input to produce oscillations or disturbances in fluid flow[1,3]. On the other hand, passive techniques are more commonly used in industries as they offer ease of implementation, simplicity and cost-effectiveness. Moreover, they do not require any external power input beyond fluid movement[1]. Passive techniques generally involve geometrical modification which increases the surface area and/or facilitates condensate removal (typically done for high Reynolds numbers[2] coiling of wired tubes around the component and incorporation of fins, fluted or grooved tubes, and wavy surfaces[1–3]. Other passive techniques include increasing roughness of surfaces and deposition of coatings[3]. Augmentation of heat transfer by increasing surface roughness is achieved by expanding the net contact area for heat exchange and by increasing the number of nucleation or precipitation sites. Surface roughness of a material can be achieved through mechanical, chemical and electrochemical methods. In terms of surface coatings, surface wettability plays a pivotal role in upgrading heat transfer performance[4]. It is assessed through the contact angle formed between condensing fluid and the surface of material[5]. For condensation heat exchangers, heat transfer through surface wettability is classified into two modes; film condensation (FC) and dropwise condensation (DwC). In FC, the condensate envelops the surface as a continuous liquid film and sheds due to gravitational force whereas DwC involves formation of discrete vapor-condensed droplets on the surface instead of formation of a continuous film. Substantial research demonstrates that dropwise condensation exhibits superior heat transfer efficiency than film condensation[5]. Another approach to enhance heat transfer is based on introduction of slippery liquid-infused surfaces (SLIPS) which are known for their high water sliding ability and surface smoothness resulting from the presence of a liquid layer[6].

In a study conducted by Ma *et al.*, it was demonstrated that steam condensation heat transfer on a hydrophobic and hydrophilic hybrid surface is approximately 23% greater compared to complete dropwise condensation. This improvement was observed at a surface subcooling of 2.0 K, with the width of hydrophobic region being around 0.55 mm. Additionally, modifying surface subcooling, maximum droplet radius and droplet size distribution with a vertically patterned hybrid surface was identified as a viable approach for enhancing and optimising condensation heat transfer performance. It was also established that heat transfer performance of steam condensation decreases with increase in width of the hydrophilic region[7]. Peng *et al.* showcased that the primary factors influencing dropwise condensation heat transfer encompass steam temperature, steam velocity, the resistance to heat transfer at the gas-liquid interface, and the presence of non-condensable gases. In this research, various micro-structured surfaces, including cylinders, cubes, cones, and pyramids, with a uniform height of 6μm were created on silicon surfaces. The study unveiled that, under equivalent conditions (steam pressure of 0.1 MPa, saturated steam temperature of 100°C, and steam flow rate at 0.298 ± 0.02 m³/h), the heat flux across all micro-structured surfaces displayed a linear increase with increase in the cooling water temperature difference and subcooling. The cylindrical micro-structured surface, having superhydrophobic properties with a contact angle $\theta = 158.4°$, displayed optimum results owing to its less sharp edges and larger contact angles[5]. In another study, a liquid-infused smooth surface, 'SPLASH' (surface with π electron interaction liquid adsorption, smoothness, and hydrophobicity) was presented as a solution to the challenges posed by rough surface structures. It was established that the maximum condensation heat-transfer coefficient of SPLASH was 175% higher compared to an uncoated substrate and it also outperformed superhydrophobic surfaces and SLIPS in terms of droplet mobility and the thermodynamic energy barrier for nucleation, resulting in superior heat transfer and more consistent dropwise condensation. Moreover, presence of a smooth base layer and the utilization of a low-viscosity infusing liquid proved to be essential factors in augmenting droplet mobility and enhancing the efficacy of heat transfer. SPLASH displayed better dropwise condensation performance and heat transfer over extended periods, compared to those achieved with rougher surfaces[6]. In a study by Lo *et al.*, a three-dimensional (3D) hybrid surface, entailing a combination of superhydrophobic silicon nanowire (SiNW) arrays and hydrophilic micro-channels, was investigated to amplify the efficiency of condensation under elevated subcooling temperatures. A notably high heat flux of 655 ± 10 kW/m² was achieved using this 3D hybrid surface. It was exhibited that the nanostructures on the 3D hybrid surfaces bolster the heat transfer coefficient whereas the micro-channels facilitate the efficient drainage of condensed droplets leading to an improve in the condensation heat transfer coefficient and heat flux[8].

Zhang *et al.*, carried out an investigation to develop prediction methods for thermal-hydraulic performance to measure frictional pressure drop and heat transfer coefficients for flow condensation in plate heat exchangers, with a specific focus on their applicability to organic Rankine cycle and heat pump systems. They evaluated seven working fluids namely hydrofluorocarbons (R134a, R236fa, and R245fa), hydrofluoroolefins (R1234ze(E) and R1233zd(E)), and hydrocarbons (propane and isobutane), for condensation temperature conditions, ranging from 30°C to 90°C. Their findings suggested that the frictional pressure drop and the heat transfer coefficient exhibit an increase with the increase in mass fluxes and a decrease with elevated condensation temperatures. This indicated that shear-controlled condensation was the prevailing mechanism throughout all working conditions. Moreover, R1233zd(E), isobutane, and R245fa demonstrated superior heat transfer coefficients than other working fluids. This was attributed to their lower vapour density and higher surface tension, which resulted in intensified convection at the interface between the liquid and vapour phases. Additionally, R1233zd(E), R236fa, and R245fa

established higher frictional pressure drops due to their larger density ratios between the liquid and vapour phases[9]. Dropwise condensation is strongly dependent on surface orientation of the condenser, where in contrast to a horizontally oriented surface, a vertically oriented surface minimizes the departure size of a droplet thus leading to an increase in heat transfer[10]. Boreyko *et al.* demonstrated that surface orientation of a condenser has a significant impact on the droplet size distribution and heat transfer of jumping droplet condensation. On the horizontal surface, the maximum droplet size achieved was Dmax ≈ 1.4 mm, whereas Dmax ≈ 160 μm was attained on the vertical surface (α = 90°). This was attributed to the inability of droplets to shed on a horizontal surface. These droplets had stuck to the surface due to gravitational return or difference in size. A vertically inclined surface allowed for the removal of trapped droplets through gravitational shedding which also removed neighbouring condensate. In a partially inclined surface, α = 45°, it was observed that large, stuck droplets rolled down the surface due to synergistic working of capillary-inertial and gravitational effects. The projected surface coverage of dropwise condensation levelled off to a self-similar value of around ε2 ≈ 0.7 for horizontal surface, ε2 ≈ 0.45 for partially inclined surface and ε2 ≈ 0.3 for vertical surface. These authors observed an enhancement in condensation heat transfer by approximately 40% and 100% for partially inclined surface and vertically inclined surface, respectively[11]. Another study by Moosavi *et al.*, utilised spraying to develop a hierarchical micro-nano coating on aluminium substrate. In their findings, the authors observed that the fabricated surface was highly superhydrophobic exhibiting a contact angle of 158° and the contact angle hysteresis observed was less than 5°. Moreover, at a surface temperature of 70°C, relative humidity of 98% and sub-cooling temperature of 25.5°C, the heat transfer coefficient of the coated sample increased by 20.6% in comparison to that of bare aluminium substrate[12].

Lee *et al.* fabricated superhydrophobic silver/silica (Ag/SiO_2) coatings on aluminium substrates using a process involving screen printing, spray-coating and co-firing. The authors compared thermal conductivity of Ag/SiO_2 coating with polyurethane/silica (PU/SiO_2) coating. Ag/SiO_2 coatings exhibited a thermal conductivity of 83.32 W/m·K which was 40 times superior to that of PU/SiO_2 coating (2.63W/m·K) thus owing to this higher thermal conductivity, faster dropwise condensation was observed in Ag/SiO_2 coatings. The superior thermal conductivity of Ag/SiO_2 coatings was because of the highly thermal conductivity Ag (K_{PU} = 429 W/m.K) in comparison to that of PU (K_{PU} < 1 W/m·K)[13]. Martucci *et al.*[14] deposited a hybrid octyl-modified silica coating on aluminium (Al) substrate using sol-gel technique and studied its thermal efficiency and durability during saturated vapour condensation. The hybrid silica-based coating constituted of 20% octyltriethoxysilane and 80% tetraethylorthosilicate (O2T8). DWC was observed on the coated aluminium surface throughout the period (7 hours) of condensation tests and a stable thermal performance was observed with the heat transfer coefficient (HTC) value of ~90 kW/m^2.K. This dropwise condensation HTC was nine-fold higher than HTC evaluated from FWC under analogous heat flux conditions by Col *et al.*[15].

This research is within the framework of a European commission project called GeoHex, where coatings are developed for commercial heat exchangers for geothermal power plants for improving efficiency, anti-scaling and corrosion performance. In particular, this paper discussed the phase II of III of the testing of coatings, more information about the project can found in reference[16]. The paper is focused on observing how parameters such as wettability or adhesion change as a function of exposure to an organic Rankine cycle (ORC) fluid (in this case, R-134a), while the thermal performance is evaluated, the results of this were used to select a coating for further trials in a commercial heat exchanger.

Methods

Heat transfer performance evaluation

In order to measure the heat transfer performance of the bare substrate and coatings materials, tests were conducted in a mock up heat exchanger device designed and fabricated by Spike Ltd, see Figure 1. This device was equipped with temperature, pressure and flow sensors, both for inlet and outlet sides of the fluids in both cooling and condensation chambers. In brief, the test consisted of passing a cool fluid by one side of the plate, and ORC fluid (R-134a) was condensed on the other side of the plate. The tests were conducted on plates of 100mm x 100mm by 6mm thickness, in vertical[1] position (allowing the rolling of the condensing fluid), see schematic of Figure 1; the testing plate itself was used to separate the water-cooled side of the system from the condensation chamber. The testing plate was fixed to the system using a bolt clamping system, and nitrile rubber O-rings for sealing. For the cold side, water was used, which was cooled in the refrigeration vessel to 5 °C, and pumped (in a close loop system) towards the cooling side of the testing plate (the flow of water ran parallel to the plate), therefore, before contacting the plate, the water temperature could be slightly increased. For the organic fluid (R134a), this was heated to ≈43 °C (in the chamber where a heating element was located), in order to reach a target temperature of ≈ 35 °C in the testing plate condensation chamber. The pressure on the condensation side was 9 bars.

The heat transfer performance was evaluated using two metrics, heat flux, denoted as q, and overall heat transfer coefficient, denoted as U. The Heat flux (or heat flux density) is a measure of energy transfer from the hot fluid to the cold fluid per unit area per unit time. It is assumed that the increase in energy in the cold fluid is equal to the decrease in energy in the hot fluid. Heat flux is calculated as:

$$q = \frac{\rho c_p \dot{V}(T_0 - T_i)}{A}, \quad (1)$$

where ρ is the cold fluid density in kg m^{-2}, c_p is the cold fluid specific heat capacity in kJ kg^{-1} K^{-1}, $\dot{V}$ is the cold fluid flow-rate in m^3 s^{-1}, A is the surface area of the substrate in m^2, and T_o and T_i are the cold fluid outlet and inlet temperatures

[1] Although some tests were conducted with the testing plate in horizontal position.

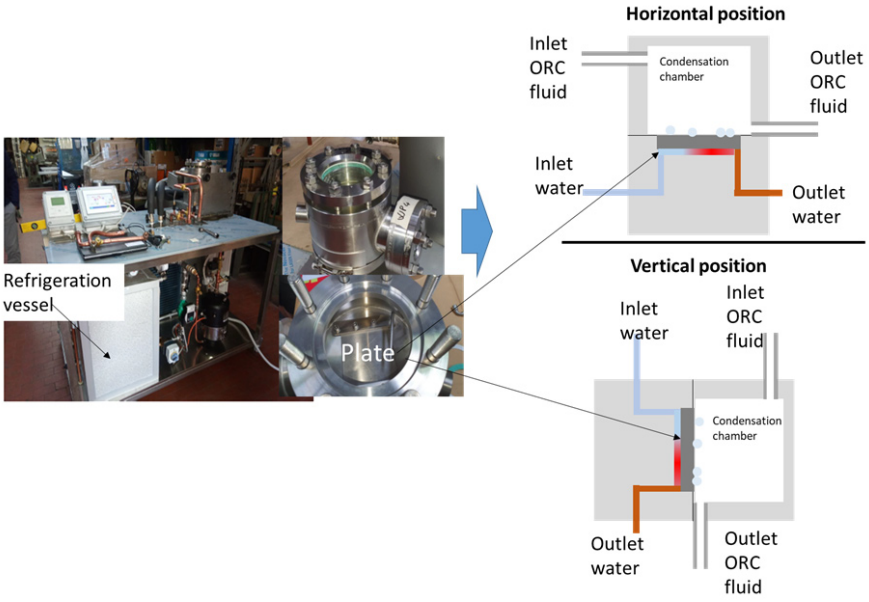


Figure 1. Photography of the fabricated heat transfer testing rig, including schematic of the testing chamber in vertical and in horizontal position.

respectively. In most cases, heat flux will be measured in kW m^{-2}.

The overall heat transfer coefficient is the proportionality constant between heat flux and temperature gradient, which in this case is the log mean temperature difference. Since the hot fluid is at saturation temperature with no large differences between inlet and outlet temperature, it is assumed that all of the energy loss in the refrigerant results in phase change. Therefore, log mean temperature difference is measured as:

$$\Delta T_m = \frac{(T_0 - T_i)}{\ln\left(\frac{T_r - T_i}{T_r - T_0}\right)}, \quad (2)$$

where T_r is the refridgerant temperature. Note that $T_r > T_o > T_i$. The overall heat transfer coefficient can be calculated as:

$$U = \frac{q}{\Delta T_m}, \quad (3)$$

Due to the small differences in the heat transfer performance indicators in some cases and due to the influence of external variables such as ambient temperature, the data was analysed statistically, this analysis is presented in the result section.

Wettability evaluation

The wettability of the surface studied was determined by performing static and dynamic contact angle measurements in deionised water and diiodomethane before and after testing; the tests were performed in a drop shape analyser DSA100 from KRÜSS. In this paper, the static water contact angle in the two selected fluids will be reported, along with the advancing (WCA [A]) and receding (WCA[R] contact angle, the contact angle hysteresis (CAH) and roll off tilt angle from the dynamic contact angle measurements.

Adhesion evaluation

To determine the adhesion of the coatings, tests according to ASTM D3359 (Standard Test Methods for Rating Adhesion by Tape Test) and to ASTM D4541 (Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers) were conducted, this last test was conducted using a Elcometer 510 Automatic Pull-Off Adhesion Gauge. For the tests according to ASTM D3359, the tape adhesion grade was qualified according to the following scale: 5B, 4B, 3B, 2B, 1B and 0B. The criteria for each definition can be found in the standard, but in summary, 5B and 4B are considered good ratings; and 1B and 0B poor ratings and the adhesion grade is determined based in the number of quadrants of the coating removed by a tape after the test is carried out.

Materials and coatings

A list of the materials and coatings used for the tests is shown in Table 1. Two different approaches were used, in order to obtain different levels of hydrophobicity, the first type of coating was an amorphous metal coating, where the surface of the bare aluminium was shifted from hydrophilic to hydrophobic without affecting the surface finish/roughness and the second type of coating was targeted to achieve superhydrophobicity (or close) by altering the surface roughness and adding low surface energy materials.

Silica based coatings

Substrate: Aluminium with 100 x 100 x 6 mm dimensions was used as a substrate.

Table 1. Test samples used for detailed heat transfer performance evaluation.

Substrate	Position	Coating side	Surface preparation	Coating type	Coating name
Aluminium	Vertical		As-received	-	
Aluminium	Vertical	Two faces	Grit blasting + degreasing + etching + anodising	Sharc® Sapphire (25%wt) + SMS35 particles (dual functionalised) (75%wt)	Sharc ® Sapphire silica
Aluminium	Vertical	Two faces	Grit blasting + degreasing + etching + anodising	Tutoprom™ (50%wt) + SMS35 particles (dual functionalised (50%wt)	Tutoprom™ Bright silica
Aluminium	Vertical	One face	As received	Amorphous hydrophobic Si:Nd:Zr	Amorphous Si:Nd:Zr

Surface pre-treatment: For a better adhesion of coating to the substrate, substrates were pretreated using the following procedure:

Step 1: Grit blasting - (aluminium oxide grit #100, 30 psi applied pressure in a position of 45°, 10 cm away from the nozzle). Grit blasting was performed in order to build-up microscale roughness (top-down modification).

Step 2: Degreasing – samples were immersed in the solution of METFIN AK 16 (NST cleaner): a cleaner that consists of tetrasodium pyrophosphate, sodium hydroxide, sodium metasilicate and distilled water, purchased from Silmid. Immersion was carried out for 15 minutes in thermal bath at 65°C (using a heater from T100 from Grant instruments).

Step 3: Etching – samples were immersed in sulphuric acid and sodium dichromate solution in thermal bath at 65°C for 30 minutes.

Step 4: Anodizing – in orthophosphoric acid solution carried out for 20 minutes.

Coating procedure: The coating procedure used can be divided into three steps, (1) Synthesis of silica nanoparticles, (2) functionalization of silica nanoparticles, and (3) reinforcement of functionalized silica nanoparticles into coating matrix.

Step 1: Silica nanoparticles were prepared using the sol-gel Stöber process[1], enables the fabrication of monodispersed, porous particles that can be made in a range of sizes. Briefly, desired amount of tetraethoxysilane (TEOS), methylated sprit (alcohol), water and ammonia were mixed with a magnetic stirrer in a sealed vessel, vigorously for four hours, followed by keeping the mixed solution undisturbed at room temperature for 24 hours. Later, the mixed solution was cleansed *via* evaporation at a rotovap Stuart model RE300DB at 65°C, where the removed solvent was replaced with fresh ethanol, this step was repeated twice before the final product was ready for evaluation. It was found by dynamic light scattering (DLS) using a malvern zetasizer that the synthesized silica nanoparticles showed monomodal size distribution with an average size of 35nm.

Step 2: Functionalisation of silica nanoparticles was done using silane coupling reagents, with aim exchanging the surface silanol groups with aliphatic hydrocarbon or fluorocarbon groups to reducing surface energy levels and promote hydrophobicity (Figure 2). The procedure used for this reaction is to mix until homogeneous (max one minute) the silica nanoparticle with a silane reagent and catalyst, and leaving overnight at 65°C inside a fume hood. To maximise the potential repellency characteristics of the nanoparticle, as close to monolayer coverage as possible is required. Here, dual functionalization of silica nanoparticles was done using Trimethoxy (3,3,3-trifluoropropyl) silane and Hexamethyldisilazane (used for Sharc® Sapphire). The functionalized silica nanoparticles are referred as SMS35.

Step 3: Two different types of coatings were used, namely Tutoprom™ Bright and Sharc® Sapphire, supplied by durxtreme and sharc ® matter respectively. Both of them are polysilazane based coating formulations which react with the surface and moisture from the atmosphere to cure, neither contain fluorine. Different wt.% of functionalised silica nanoparticles were incorporated into these matrices (Table 1).

The coating formulation was applied on the substrate *via* dip coating with a speed of 100 mm/min, followed by the curing as per manufacturer's guidance.

Amorphous coating. The amorphous metal coatings were prepared by direct current magnetron sputtering (dcMS) from 4" diameter circular planar magnetrons in a custom-built high vacuum deposition system with a base pressure of the order of 10^{-6} mbar. The coatings were deposited onto aluminium substrates (100 x 100 mm^2) which were cleaned in acetone and isopropanol prior to being inserted into the vacuum system. Before deposition, a radio-frequency plasma etch (100 W for 15 minutes at 30 sccm Ar flow) was performed *in-situ* to

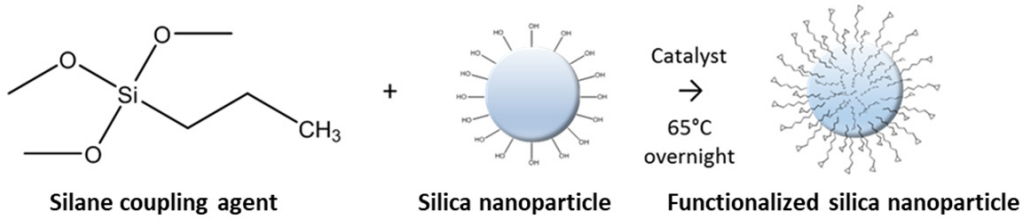


Figure 2. Functionalization of silica nanoparticles.

remove the native surface oxide. This mild etch should not introduce any significant surface roughness. Sputtering was carried out in an Ar flow of 40 sccm which resulted in a chamber pressure of $3.6x10^{-3}$ mbar. First, a 200-nm-thick Cr layer was deposited from a 99.9% pure Cr target to promote adhesion to the substrate. Subsequently, the 1-μm-thick Si:Nd:Zr layer was grown from a composite target of 99.9% purity with an applied magnetron power of 600 W. The samples were placed on a rotating sample holder and were continuously rotated during growth to ensure thickness uniformity. No substrate heating was employed, in order to avoid the crystallisation of the Si:Nd:Zr film. Nonetheless, a bias voltage of 100 V was applied to the sample holder throughout to increase density and adhesion but this did not result in crystallisation. This was confirmed by x-ray diffraction (XRD) measurements in both grazing incidence (GiXRD) and standard θ-2θ geometry in a Panalytical Empyrean x-ray diffractometer. XRD measurements are employed both to confirm the absence of clear peaks corresponding to crystalline phases but will also display the characteristic broad peak or halo associated with the amorphous structure of the material. This halo was observed clearly in all cases.

The selection of the Si:Nd:Zr alloy described here is the result of a comprehensive screening of a range of compositions to optimise for hydrophobicity. Combinatorial methods were employed whereby samples with composition gradients were fabricated and characterised in terms of their amorphicity, corrosion resistance and hydrophobicity. The combinatorial optimisation procedure is described in detail in Reference 17 for similar amorphous ternary alloy systems. The substrate preparation procedure was designed to emphasise the effects of coating composition on hydrophobicity, irrespective of surface morphology. Future implementations could aim to apply this coating to a surface with the multiscale roughness needed for superhydrophobicity.

Statistical analysis of the data

To determine the heat transfer performance indicators, statistical analysis over the data was performed. The preliminary analysis started with time series analysis. The important time series measurements for heat transfer evaluation are water inlet and outlet temperatures, refrigerant temperature, and flowrate. Each of these measurements were taken ten seconds apart, and therefore adjacent measurements are highly correlated (*i.e.*, a high degree of association). Hourly averages (mean) were determined in order to get a more statistically independent sample. This made adjacent raw measurements like T_o and T_i (see section heat transfer performance evaluation for notation) no longer significantly correlated, see Figure 3a (and b). However, the calculated metrics q and U were still showing high levels of autocorrelation (*i.e.*, correlation between adjacent measurements), see Figure 3 (c and d). This is not surprising as T_o is strongly and similarly affected by T_i, so variables dependent on their difference have much less variation and show more subtle patterns (like the ambient temperature effect).

It is obvious from the autocorrelation graphs in Figure 3 that q and U variables have a cyclic measurement effect with a 24-hour cycle. Ambient temperature, Figure 4, has a very similar autocorrelation graph, so it was decided that the ambient temperature is an important covariant that should be taken into account in the analysis.

As seen from Figure 5, ambient temperature seems to have a negative impact on the measurements of the heat transfer performance metrics (in other words, when ambient temperature increases heat transfer performance decreases). One possible explanation for this is that although T_o and T_i are both affected by ambient temperature, T_i is more affected by ambient temperature, as it is lower than T_o.

Figure 6 shows the graphs of q and U by ambient temperature, along with the best-fit lines. By inspection, these graphs indicate a strong linear relationship. We use two metrics to determine the strength of a linear relationship. The first metric is the coefficient of determination, R^2, which is a measure of correlation strength ranging from 0% to 100%, with 0% indicating no correlation and 100% indicating perfect correlation. The second metric is the p-value from an F-test comparing a linear model to a random model, which is a measure of the significance of the linear model. The F-test is a standard test to determine the statistical significance of the linear relationship by comparing the variance about the mean to the variance about the line. The p-value can be thought of as a probability of seeing the data assuming a random model instead of a linear one. The smaller the p-value, the more significant the linear relationship. We will consider the linear relationship to be statistically significant if the p-value is less than 0.05. An explanation of both of these metrics and the F-test is provided by Draper *et al.*[18].

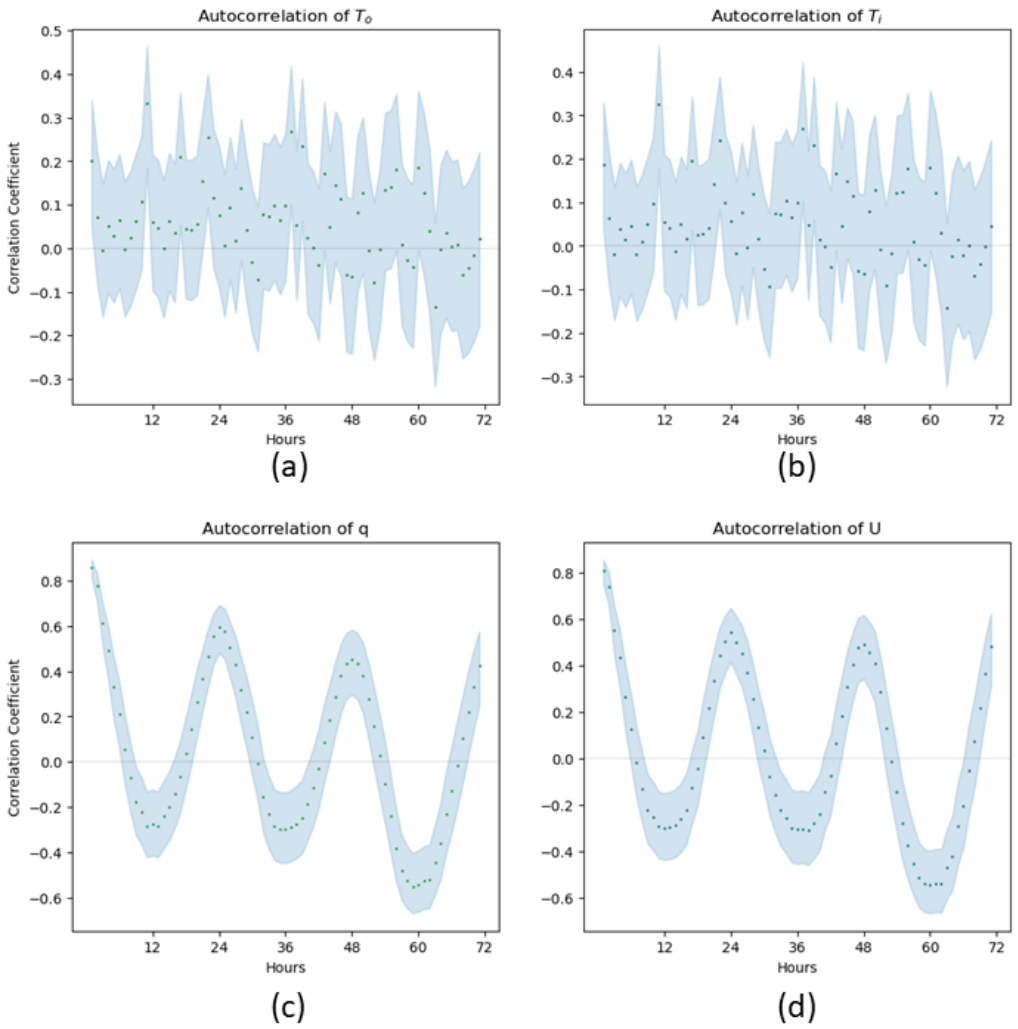


Figure 3. Autocorrelation Graphs of horizontal bare aluminium measurements with 95% confidence intervals indicated by blue shading.

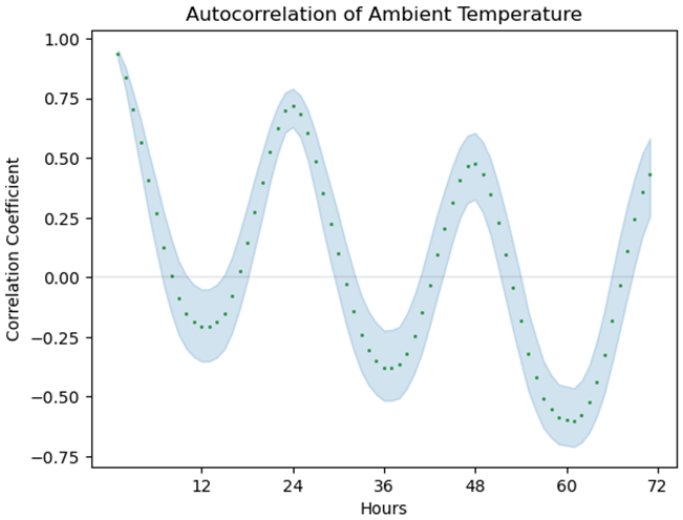


Figure 4. Autocorrelation graph of ambient temperature during the horizontal bare aluminium test with 95% confidence intervals indicated by blue shading.

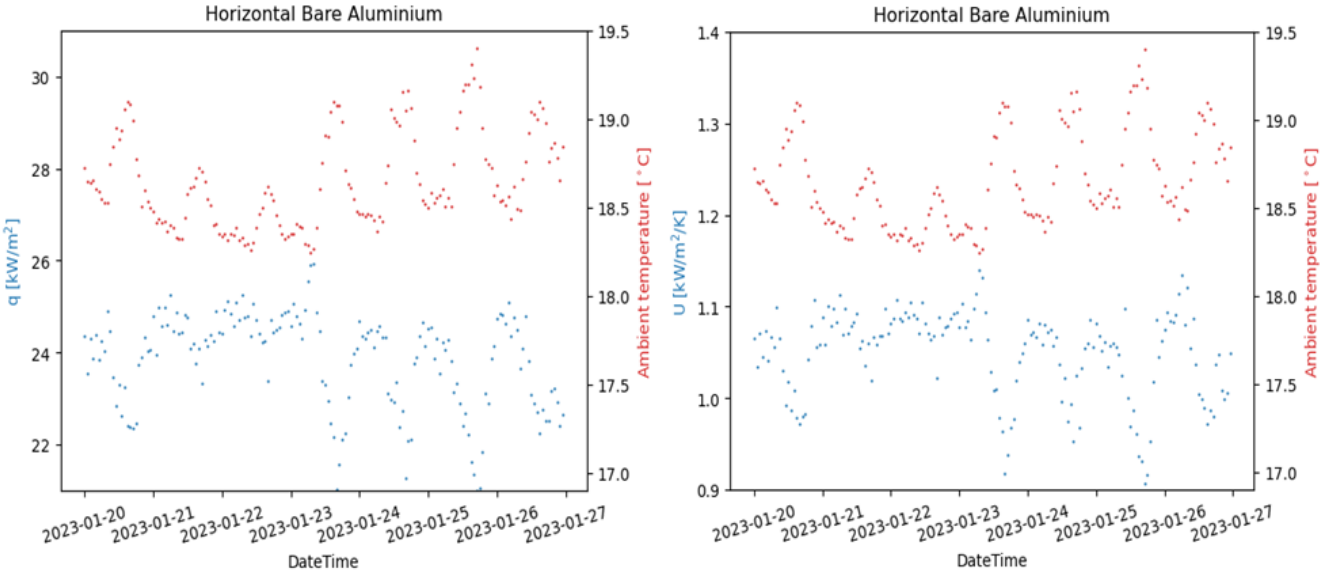


Figure 5. Heat transfer performance and ambient temperature by time.

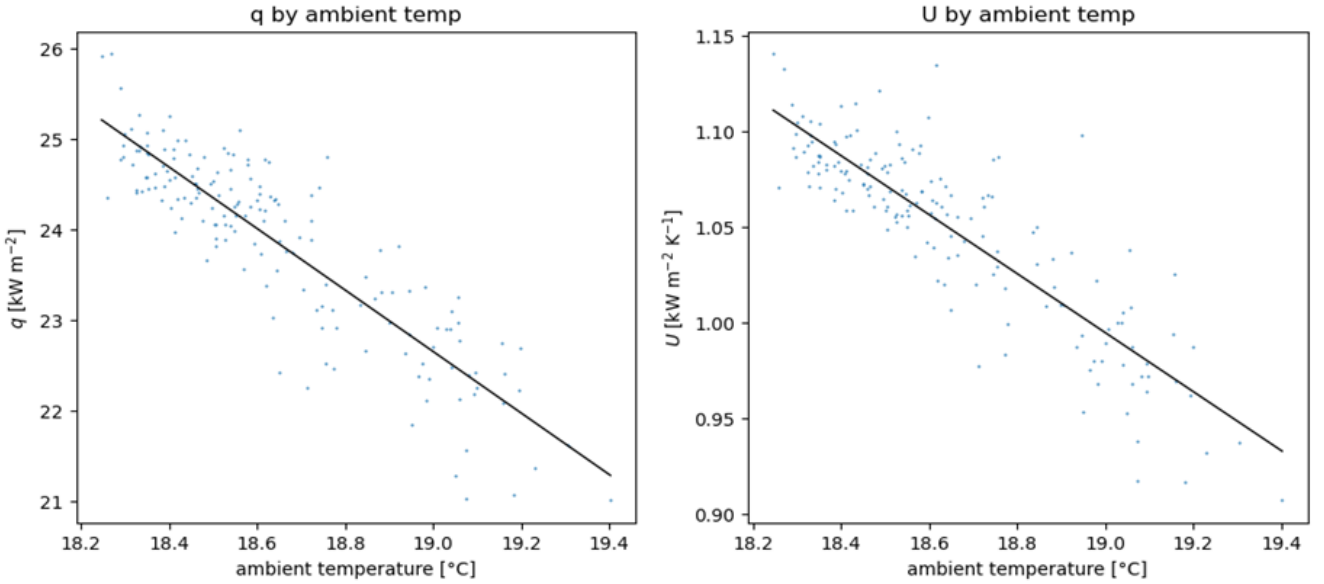


Figure 6. Heat transfer performance by ambient temperature.

In the case of Figure 6, R^2 was 78% for q and 75% for U. In both cases an F-test comparing this linear model with a random model gave a p-value<0.001, meaning that this relationship is statistically highly significant. When this linear relationship was taken into account, the residuals (the data minus the best-fit line) were approximately normally distributed and have much less significant autocorrelation (correlation between subsequent hourly means), see Figure 7 and Figure 8.

Another important factor is degradation of heat exchange performance over time, an example of which is shown in Figure 9. This was most pronounced in the first day of the experiment, but can last longer. When choosing a sample, inspection of q and U (and their respective residuals) by time was used in order to adopt as much data as possible that did not include performance degradation. In cases when performance degradation lasted for the whole experiment, 48 hours of the

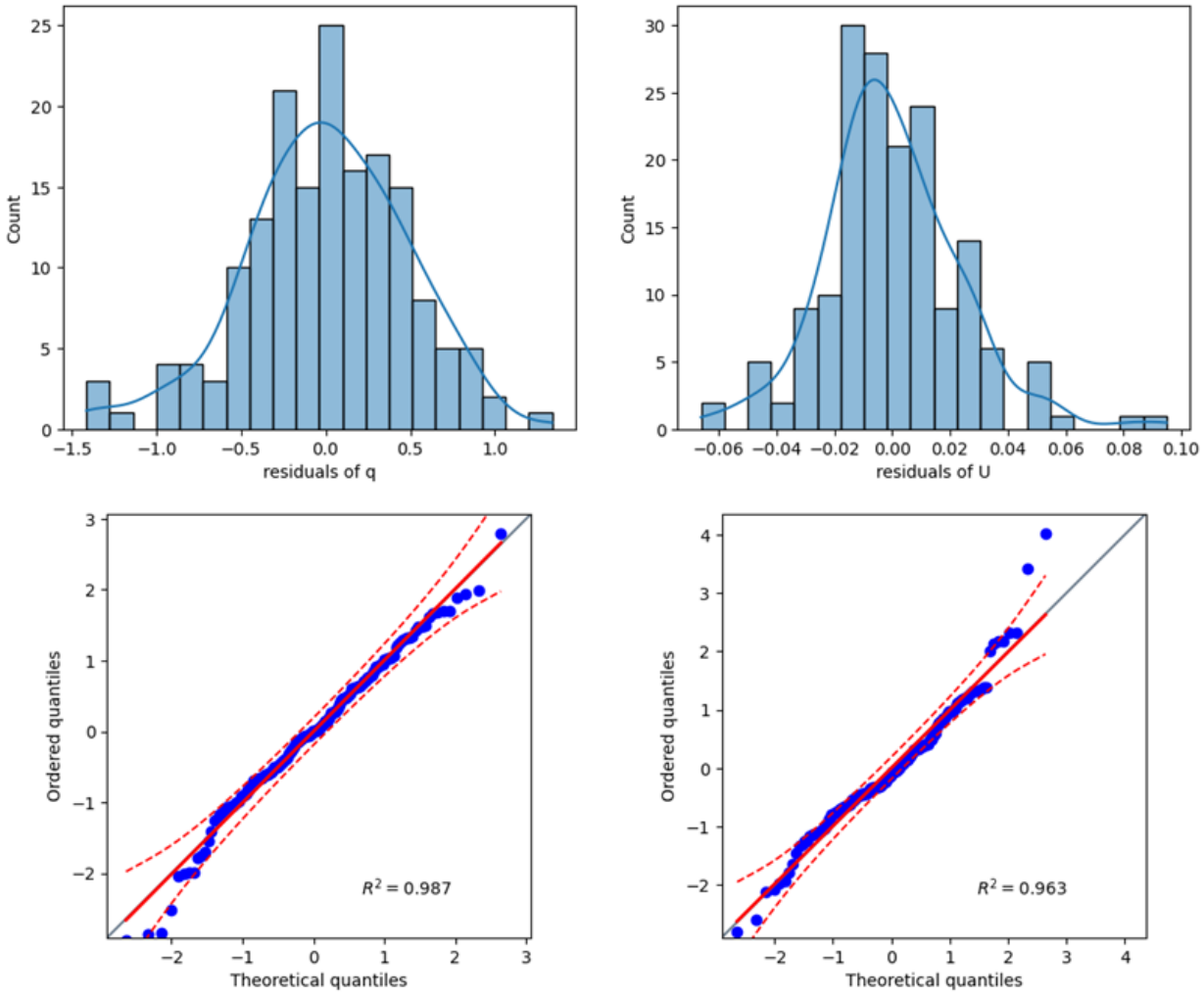


Figure 7. **Distribution of residuals on horizontal bare aluminium.**

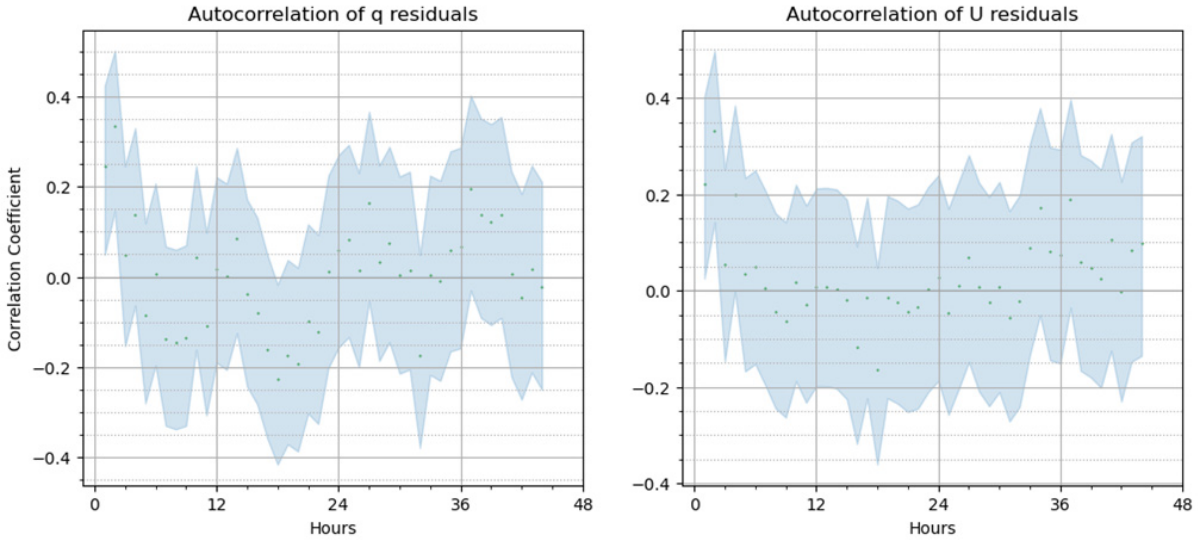


Figure 8. **Autocorrelation of residuals on horizontal bare aluminium with 95% confidence interval.**

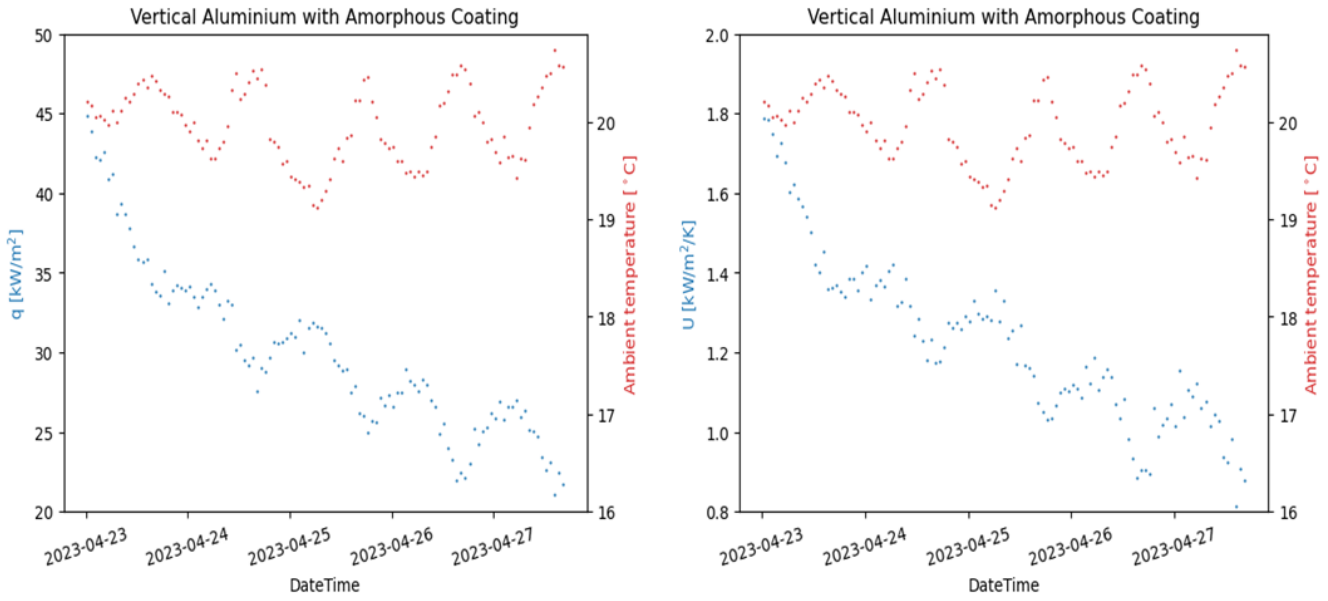


Figure 9. A different experiment demonstrating performance degradation over time.

best continuous data were chosen with preference for data towards the end of the experiment.

After choosing the sample of hourly means from a continuous time period, the sample was assessed for a linear relationship with ambient temperature using an F-test. If there was a statistically significant linear relationship with ambient temperature, the residuals were assessed for normality and autocorrelation. Non-linearity was tested with an F-test comparing the linear model with a quadratic model. Confidence intervals denote the confidence on the linear regression[18].

If there was no statistically significant relationship with ambient temperature, the sample was assessed for normality and autocorrelation. Confidence intervals denote confidence in the population mean using a t-distribution. This is because the mean of a small sample is t-distributed[18].

In both cases, normality was tested with a quantile-quantile plot (Q-Q plot) comparing the data to a perfect normal distribution. The straighter the line on the Q-Q plot, the better it fits a normal distribution. If the line is within a 95% confidence interval, the distribution is approximately normal, see Figure 7 for an example. Autocorrelation was tested with an autocorrelation graph. The closer this graph is to random variation, the less correlated adjacent hourly means are, see Figure 8 for an example. These graphs are often included as figures in this report, especially if there is something to note about them. When confidence intervals did not intersect, a statistically significant difference existed. If confidence intervals did intersect, statistical tests were used. All tests were conducted at a significance level of 0.05.

Any statistically significant improvements observed were followed up with an approximation of the effect size and a judgement on whether this improvement has practical significance. Statistical significance was measured with a p-value and practical significance was assessed from the size of the effect.

Heat transfer performance evaluation

Figure 10 compares the performance of bare aluminium with against the samples with the different type of coatings, as a function of the outer room temperature. Note: the data in Figure 10 was presented this way because it was found that the heat transfer performance indicators were affected by the ambient temperature *i.e* q and U variables have a cyclic measurement effect with a 24-hour cycle, therefore, the ambient temperature is an important covariant that should be taken into account in the analysis. In addition, it is worth noting that ambient temperature seems to have a negative impact on the measurements of the heat transfer performance metrics (in other words, when ambient temperature increases heat transfer performance decreases). One possible explanation for this is that although T_o and T_i are both affected by ambient temperature, T_i is more affected by ambient temperature, as it is lower than T_o. In relationship to the results itself, as observed in Figure 10, none of the confidence intervals overlap and so each coating results in a statistically significant difference in heat performance. All the original heat transfer data can be found in reference 19

A summary of presented results shown in Figure 10 is presented in Table 2. The summary statistics for the uncoated material are the regression values at the midpoint ambient temperature. The summary statistics for the coated material are

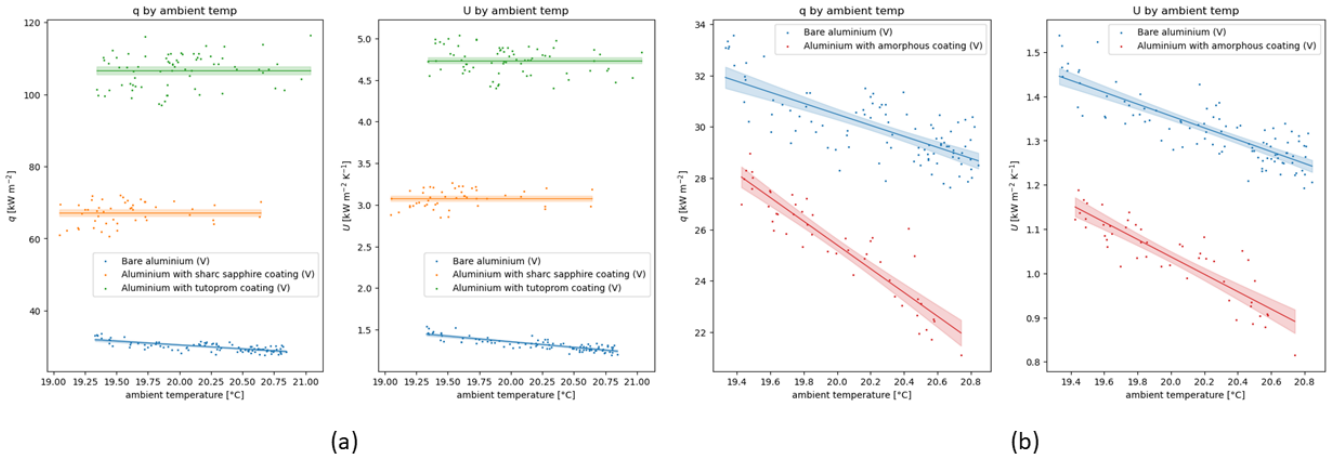


Figure 10. A comparison of the heat transfer performance indicators q and U as a function of the ambient temperature for the (**a**) silica-based coatings and (**b**) the amorphous metal coating.

Table 2. Performance metrics for aluminium under condensing heat transfer.

Coating	q [kWm^{-2}]	Percentage difference from uncoated	U [kWm^{-2}K^{-1}]	Percentage difference from uncoated
None (aluminium substrate)	30.3		1.34	
Sharc® sapphire	67.2	+120%	3.08	+127%
Tutoprom™ bright	106.6	+252%	4.74	+253%
Amorphous	25.0	-17.5%	1.02	-24.1%

the regression values at the midpoint of the ambient temperatures measured in both the coated experiment and the uncoated experiment. Based on the values used for the comparison, in Figure 10a it can be observed that the silica-based coatings in aluminium (Sharc ® Sapphire silica and Tutoprom™ bright silica), offer an increase in the heat transfer performance, the increase in performance can be up to 253%. When the comparison was established against the amorphous hydrophobic Si:Nd:Zr coating, a decrease of ≈17.5% and ≈24% was observed in the heat transfer performance indicators.

Wettability evaluation

All the coatings tested are hydrophobic (see properties before testing), water contact angle larger than 90°, and some of them (Sharc® Sapphire silica and Tutoprom™ bright silica) are almost super-hydrophobic, with contact angle hysteresis and roll-off tilt below 10°, and water contact angle very close to 150°. The situation is different in diiodomethane, where all the values are lower.

In terms of the durability of the wetting properties, the values of the water and diiodomethane contact angle obtained before and after exposure to ORC fluid for 200 hours are reported in Table 3 and Table 4. A representation of the results can be seen in Figure 11 for the static measurements. From the column graphs (Figure 11), it can be noted that for all the coatings, the hydrophobicity decreased after exposure to the ORC fluid, the largest difference is in any case below 10%. The decrease in fluid-phobicity is more accentuated in the measurements in diiodomethane, where the decrease is higher, again, in the sample coated with Sharc® Sapphire silica.

From the measurements obtained from the dynamic contact angle tests Table 4, in the samples coated with the silica-based coatings (tutoprom bright™ silica and sharc® sapphire silica), a considerable increase was seen in the roll-off tilt angle in water after exposure to the ORC fluid, however, the differences are not so significant when measured in diiodomethane. When the measurements were performed in the amorphous coating, the first observation is that this produced a low roll-off tilt angle before testing diiodomethane, this very low value increase after exposure to the ORC fluid. No degradation in the roll-off tilt angle was seen in this coating after measurements using water as the probe liquid. A peculiar observation is that the roll-off tilt angle reduced in diiodomethane after exposure to the ORC fluid for the bare aluminium plate.

Adhesion strength

For all cases, the tests carried out by ASTM D3359 (tape adhesion), the coatings displayed a good adhesion strength before and after exposure to the ORC fluid, see Table 5.

Table 3. **Performance metrics for aluminium under condensing heat transfer.**

Substrate /coating name		Water contact angle	St Dev	Diiodomethane contact angle	Standard deviation
As received Bare aluminum	**before**	80.95	6.47	53.95	3.85
	after	79.82	9.54	58.04	2.52
Rough Aluminium/Sharc® sapphire silica	**before**	148.19	0.32	109.63	0.21
	after	134.39	1.06	85.06	4.72
Rough Aluminium / Tutoprom™ bright silica	**before**	146.04	1.46	98.67	0.17
	after	139.22	1.36	80.52	17.88
As received Aluminium /amorphous Si:Nd: Zr	**before**	100.38	2.0	63.15	4.7
	after	93.38	0.72	47.1	1.79

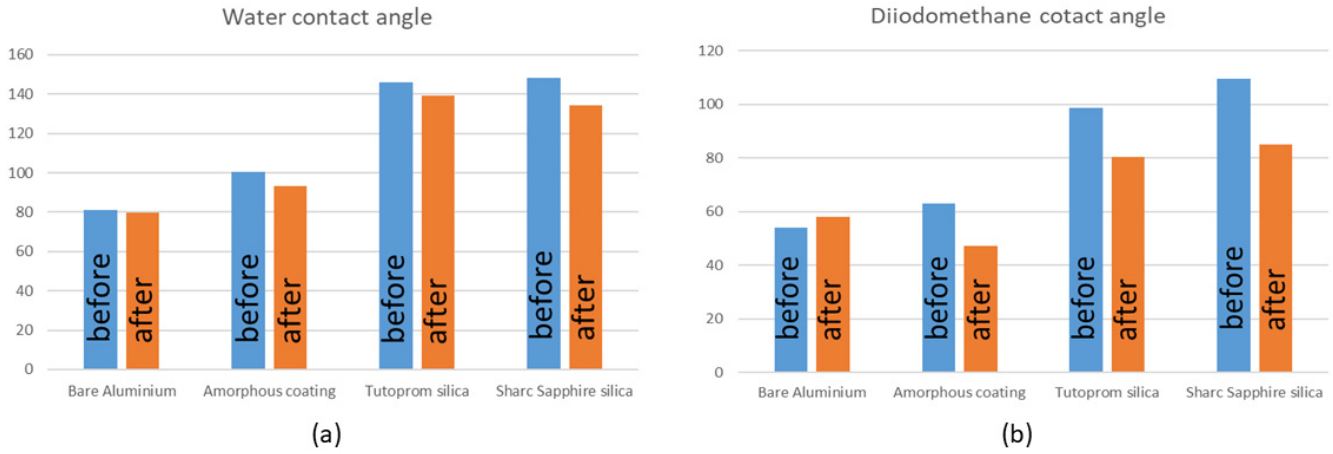


Figure 11. Static contact angles before and after testing (in ORC fluid condensation tests) in (**a**) water and (**b**) Diiodomethane.

Table 4. **Dynamic contact angle with water and diiodomethane as the probe liquids in samples developed in D3.2 to D3.5 before and after exposure to R-134(a) in condensation tests.**

Substrate /coating name		Roll-off tilt (o)[1]	WCA [R] (o)[1]	WCA [A] (o)[1]	CAH (o)[1]	Roll-off tilt (o)[2]	DCA [R] (o)[2]	DCA [A] (o)[2]	CAH (o)[2]
Aluminium	**before**	80	77.62	102.53	24.91	26.36	36.99	74.73	37.74
	after	89.38	54.31	84.59	30.28	18.76	16.95	60.67	43.72
Aluminium/ Sharc® sapphire Tutoprom™ bright	**before**	5	139.5	141	1.5	30.5	29.5	113	83.5
	after	39.48	118.90	134.15	15.3	49.05	32.46	128.53	96.07
Aluminium / Tutoprom™ bright	**before**	17	126	133.5	7.5	32	26	113.5	87.5
	after	39.58	117.36	132.92	15.6	36.71	34.23	104.87	70.64
Aluminium /amorphous Si:Nd:Zr	**before**	79.57	59.67	87.08	27.41	12.11	41.08	76.39	35.31
	after	80	65.33	90.32	25	37.83	46.7	89.95	43.25

[1] *water*

[2] *diiodomethane*

Table 5. Tape adhesion and pull-off tests of in the coated samples before and after testing according to ASTM D3359 and ASTM D4541.

Substrate /coating name		Tape adhesion grade	Dolly pull-off	
			Strength [MPa]	Failure location
Aluminium/ Sharc® sapphire	before	4B	0.22	Coating-substrate interface adhesion failure
	after	4B	1.84	
Aluminium / Tutoprom™ bright	before	4B	NA	Glue failure, coating too repellent to be tested
	after	4B	2.33	
Aluminium /amorphous Si:Nd:Zr	before			
	after	4b	1.33	

Regarding the tests conducted in accordance to ASTM D4541, the strength of the Sharc® Sapphire coating was noticeably low before exposure to the ORC fluid. Given that there is no mechanism to explain an increase in bonding strength of the coating after exposure to R134(a), and given that the strength of the other Sharc® Sapphire formulation used during the coating developing process was between 1.03MPa and 1.26MPa, it is assumed that this could be a measurement error. For the Tutoprom™ bright coating, this was too repellent for measurements to take place before exposure to the ORC fluid, for this reason, the measurements were only taken after. For the Amorphous Si:Nd:Zr coating, no value was acquired before tests. For all these reasons, it was difficult to assess the durability of the adhesion strength of the coatings developed in this program. In addition to this, no compliance value was found for coatings for heat exchanger applications, as a reference, for protective coatings in concrete, a minimum adhesion strength from 1.4 to 1.75 MPa is recommended[20], the values of adhesion strength of the coating developed in this project are within this range on aluminium, however, using the same silica based coatings but for stainless steel and copper, the values of adhesion strength was between 7.87MPa and 10.07MPa.

Discussion

The results of this work can be divided into different stages, one that relates to the characterization of the surface *i.e.*, wettability measurements, or adhesion, another relates to the durability of the coatings as a function of the exposure to a refrigerant and finally how improving the mode of condensation in a surface from film-wise condensation to dropwise condensation can assist in the decrease of thermal resistance to improve heat transfer. The objective of the work at this moment is not to explain the gaps between these stages, rather to make observations and highlight them.

In terms of the wettability, based on the literature, for example, the book written by Yee Law and Zhao[21], it would seem than even more important for this application than the static contact angle, is the angle of tilting at which the droplet start moving. From these measurements, from the measurements in water, it is observed that the sharc® sapphire coating has the lower roll-off tilt angle, therefore, it would be expected, based on this parameter, that this coating presented the better dropwise condensation[2]. If the heat transfer was based on the drop mobility on diiodomethane, then the amorphous coating should have the better heat transfer performance indicators. However, when heat transfer condensation tests were conducted, Tutoprom™ bright presented the better behaviour. It should be noted that at this stage, we did not expect a one to one correlation, either between water-phobicity or diiodomethane-phobicity and heat transfer performance indicators, as the wetting properties that can be obtained in a refrigerant, and at a different pressure, can be quite different, for example, the surface tension of water can be between ≈30 and ≈5 greater than the surface tension of a refrigerant[22]. This is certainly a gap during the stage of developing of the coatings, in agreement with other investigations in the topic[23]. However, the wetting properties in water seem to be more adequate for the estimation of the properties in the ORC fluids (at least in R-134A).

Regarding the durability of the coating, there are three aspects of consideration: (i) Adhesion strength, (ii) wettability and (iii) and heat transfer performance. The last two will be analysed in conjunction. With respect to the adhesion strength, not much can be said, given the difficulties presented for obtaining those measurements. However, the values measured after testing were no different to the average values obtained during the developing of the coatings (from the different formulations, which ranged from 0.81MPa to 1.49MPa)[24], therefore, it can be said that the ORC fluid did not affect the adhesion strength of the coatings. Equally, it would be irresponsible to say that this is good enough, given that is an application where a fluid is travelling at high speed, and adhesion strength is very relevant. Regarding the heat transfer performance over time, Figure 12 shows how this changed. At the beginning of the tests, a sharp drop is seen for all the samples (Coated and uncoated), the reason for this is unknown, however, given that this is not specific to the coating, this part of the curve will not be analysed. Still, in the "steady state region", a variation over time in the heat transfer performance can be observed, this variation includes the cyclic effects associated

[2] Note: Amorphous coating were selected for this study due to these are metallic coating, therefore exerting the lower thermal resistance barrier.

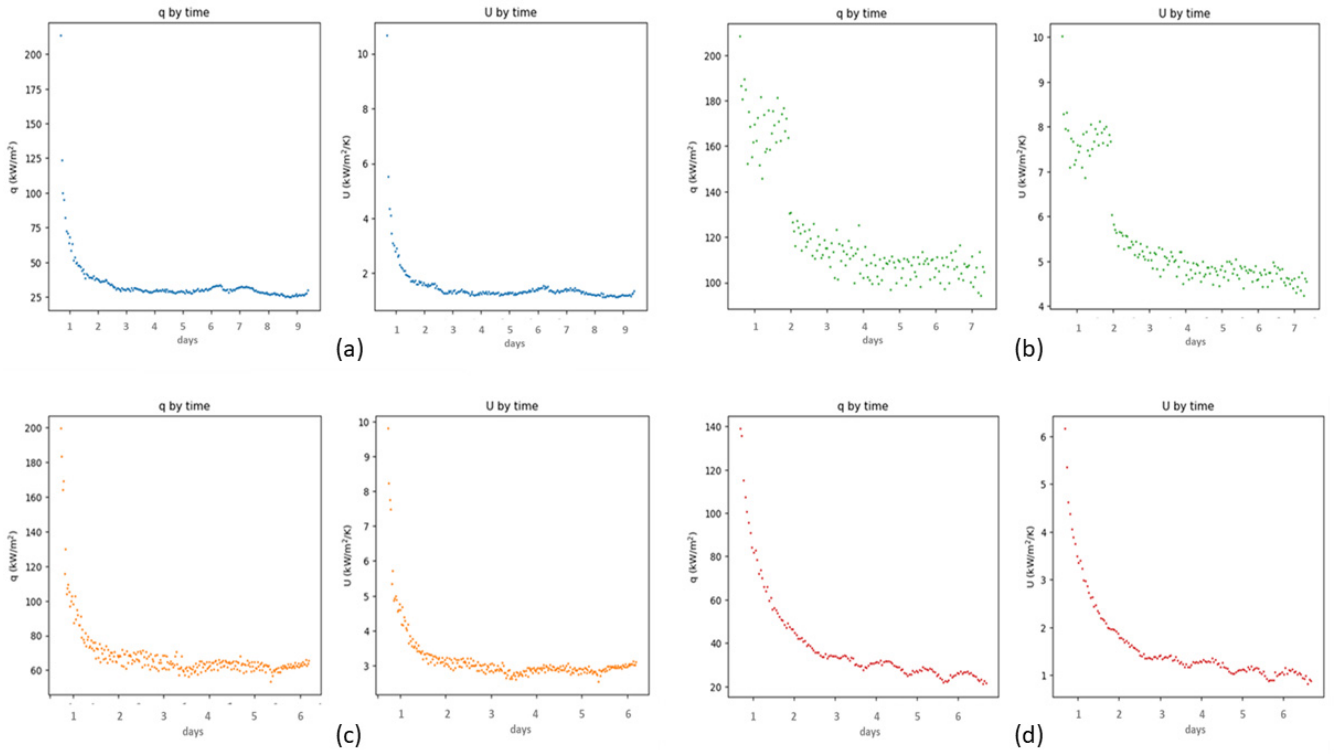


Figure 12. Heat transfer performance indicators q and U over time duration of the tests for (**a**) uncoated aluminium, (**b**) Tutoprom ™ bright, (**c**) Sharc® sapphire and (**d**) amorphous Si:Nd:Zr coating.

to day and night (ambient temperature), as explained before, although these are not the only changes present. For example, the curve of overall heat transfer performance U for the sample coated with Tutoprom™ bright display what appears to be visually a decrease over time, this behaviour is similar for the sample coated with amorphous Si:Nd:Zr coating. In the Tutoprom ™ bright coated specimen, the scatter is larger than in the other cases. For the sharc® Sapphire coating sample, the behaviour in the time observed finished with an upward trend. Despite all these different observations, in any case, for each sample, the variation in the heat transfer indicators in the time observed overlaps with the heat transfers indicators of the other configurations. Now, if we try to link the heat transfer performance to the wetting behaviour, the results indicate that there was a reduction in the fluid-phobicity of all the coatings after exposure to the ORC fluid, which as shown, not necessarily correlate with the performance of the heat transfer performance indicators over time. Given that there could be also other factors affecting the heat transfer performance indicators, *i.e.*, fouling on the side of the sample exposed to water, we consider that there must be a fluid-phobic threshold value at which at increase in the properties can be seen, and that if you do not cross this value, the change in the performance is not going to be significant.

Another factor that indicates that the coatings are not degrading during the duration of the test is that the visual aspect of this does not change after exposure to the ORC fluid, this is not surprising given that this is a refrigerant with no other contaminant. Given that water is other working fluid for thermal applications, we exposed coated samples (with the same formerly mentioned coatings) to condensation conditions in water at 60°C for ≈200 hours, the images of before and after exposure are shown in Figure 13. Again, the coatings displayed no visual affection by the working fluid.

Finally, regarding the improvement in the heat transfer condensation, two levels of coating were developed, one with microscale roughness and low surface energy materials to achieve very high levels of hydrophobicity and the other hydrophobic, with the same surface finish as the as received bare aluminium. Based on the observations of the heat transfer performance, we attribute, as based in the current knowledge, the increase in performance to the change in the transfer mode, when high levels of fluid-phobicity are reached. This is also because sharc® sapphire silica and tutoprom ™ bright silica are polymeric coatings, therefore, they are actually thermal barriers and the thermal performance should be less if no other change in the system is provided. However, as mentioned in the introduction, there are also other aspects of the dropwise condensation mode that also affect the heat transfer *i.e.*, mobility of the droplets, size of these, sub-cooling, among others. To explore one of these variables, a test was conducted with the system in horizontal position, see results in Table 6. Mukherjee *et al.* explain in detail the mechanism

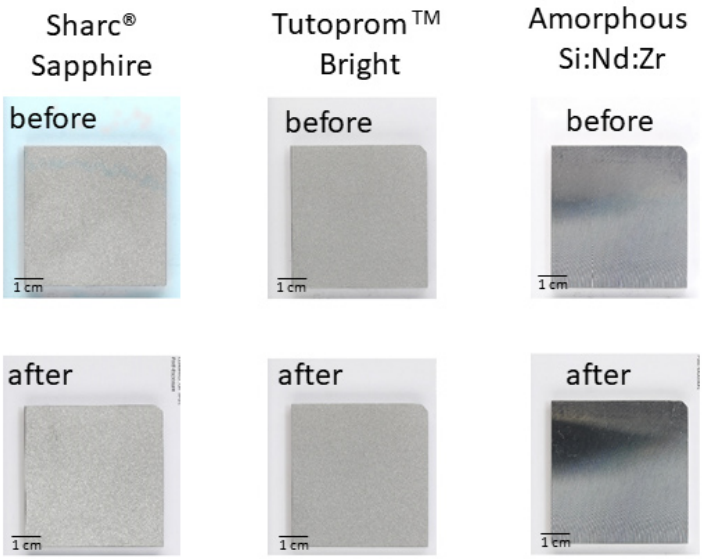


Figure 13. Images of the coatings before and after being exposed to condensation in water at 60°C. These conditions were chosen because they were considered more aggressive than exposure to the ORC fluid at 35°C.

Table 6. Heat flux (*q*) and overall heat transfer coefficient (*U*) for the uncoated aluminium plate in vertical and horizontal position.

Sample	position	*q* [kWm^{-2}]	*U* [kWm^{-2}K^{-1}]
Uncoated aluminium	Vertical	30.3	1.34
Uncoated aluminium	Horizontal	23.2	1.02

by which the surface orientation plays a role in heat transfer experiments[11]. In brief, orientation will have an enhanced effect due to two interlinked factors; in hydrophobic surfaces, (i) the condensation droplets will jump out of the solid/condensation plate, the distance of the jump will depend on the level of hydrophobicity of the surface (size of the departure droplet), and in the presence of vertical surfaces, (ii) the gravitational shedding will cause a larger jump of the droplet or its complete removal from the surface. Vice versa, in horizontal surfaces, a jumping droplet could fall into the same plate until eventually get stuck, due to coalescence with other droplets. From the very small changes in the heat transfer performance indicators shown in Table 6, it can be concluded that mobility of the droplets/orientation is not very important but if couples with dropwise condensation, this can have a major impact.

The reason why this study is not intended to understand all the gaps between the relationship between wetting and heat transfer mode is that there are many variables that play a role. And it is not very easy to assess all of these in laboratory tests, just to give an example, in a geothermal power plant, condensation will take place after the working fluid is coming from the turbine at very high speed, this is difficult to implement in a laboratory study. Investigating all these parameters could be time consuming and with no guarantee that will lead to heat exchangers with improved efficiency. However, in this project, we will actually use commercial heat exchanger to tests the coatings developed in the program; this new information will be used to feedback our coating development process in a more pragmatic way and with more certainties.

Conclusions

In this study, the surface of aluminium plates was modified to increase the heat transfer performance. In the medium level of hydrophobicity samples (coated with Amorphous Si:Nd:Zr), no increase in the heat transfer performance indicators was achieved with small reduction in the q and U parameters. In the very high hy-drophobicity level samples (silica coated samples with high roughness), an increase in the thermal performance indicators was observed. All the materials displayed excel-lent durability in the mild environment that presented. Given the results of this study, a logical future line of investigation would be if a metallic coating (good thermal conductivity) is added to a nano-hierarchical surface (this can lead to enhanced hydrophicity), is a candidate coating material for an application that require high heat transfer for condensation heat exchanger.

Ethics and consent statement

No ethical approval or consent were required.

Data availability

Underlying data

Zenodo: Investigation of the effects surface alteration via coatings on the condensation heat transfer and wettability. https://doi.org/10.5281/zenodo.10148496[19]

This project contains the following underlying data:

- contact angle measurements before (Folder containing: pdfs documents of the data provided by the KRÜSS contact angle measurements equipment)
- contact angle measurements after (Folder containing: pdfs documents of the data provided by the KRÜSS contact angle measurements equipment)
- Heat transfer data (Folder containing: excel sheets for each day of testing for the sensors of water inlet and outlet temperature, pressure of the condensation chamber and flow of ORC fluid and water. With some excels sheets showing process data for easier interpretation of results)
- adhesion results 2.xlsx (File containing: excel file containing Images of the samples after adhesion tests)
- adhesion results.xlsx (File containing: excel file containing Images of the samples after adhesion tests)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Acknowledgments

We want to acknowledge the contribution of the GeoHex consortium to this project. Especially to Friðrik Magnus.

References

1. Mousa MH, Yang CM, Nawaz K, *et al.*: **Review of heat transfer enhancement techniques in two-phase flows for highly efficient and sustainable cooling.** *Renew Sustain Energy Rev.* 2022; **155**: 111896.
Publisher Full Text
2. Attinger D, Frankiewicz C, Betz AR, *et al.*: **Surface engineering for phase change heat transfer: A review.** *MRS Energy & Sustainability.* 2014; **1**: E4.
Publisher Full Text
3. Tabatabaeikia S, Mohammed HA, Nik-Ghazali N, *et al.*: **Heat transfer enhancement by using different types of inserts.** *Adv Mech Eng.* 2014; **6**: 250354.
Publisher Full Text
4. Ahlers M, Buck-Emden A, Bart HJ: **Is dropwise condensation feasible? A review on surface modifications for continuous dropwise condensation and a profitability analysis.** *J Adv Res.* 2019; **16**: 1–13.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**
5. Yao Y, Peng Y, Wu X, *et al.*: **Dropwise condensation heat transfer of the surface with micro columns.** *Energy Reports.* 2022; **8**: 8883–8895.
Publisher Full Text
6. Tsuchiya H, Tenjimbayashi M, Moriya T, *et al.*: **Liquid-infused smooth surface for improved condensation heat transfer.** *Langmuir.* 2017; **33**(36): 8950–8960.
PubMed Abstract | **Publisher Full Text**
7. Peng B, Ma X, Lan Z, *et al.*: **Experimental investigation on steam condensation heat transfer enhancement with vertically patterned hydrophobic–hydrophilic hybrid surfaces.** *Int J Heat Mass Transf.* 2015; **83**: 27–38.
Publisher Full Text
8. Lo CW, Chu YC, Yen MH, *et al.*: **Enhancing condensation heat transfer on three-dimensional hybrid surfaces.** *Joule.* 2019; **3**(11): 2806–2823.
Publisher Full Text
9. Zhang J, Elmegaard B, Haglind F: **Condensation heat transfer and pressure drop correlations in plate heat exchangers for heat pump and organic Rankine cycle systems.** *Appl Therm Eng.* 2021; **183**: 116231.
Publisher Full Text
10. Koch G, Zhang DC, Leipertz A: **Condensation of steam on the surface of hard coated copper discs.** *Heat Mass Transf.* 1997; **32**(3): 149–156.
Publisher Full Text
11. Mukherjee R, Berrier AS, Murphy KR, *et al.*: **How surface orientation affects jumping-droplet condensation.** *Joule.* 2019; **3**(5): 1360–1376.
Publisher Full Text
12. Rezaee B, Taheri MM, Pakzad H, *et al.*: **Enhancement of Dropwise Condensation Heat Transfer through a Sprayable Superhydrophobic Coating.** *Langmuir.* 2023; **39**(23): 8354–8366.
PubMed Abstract | **Publisher Full Text**
13. Sasidharanpillai A, Kim D, Lee Y, *et al.*: **Highly thermally conductive Ag/SiO2 superhydrophobic coating for accelerated dropwise condensation.** *Ceram Int.* 2021; **47**(18): 26528–26538.
Publisher Full Text
14. Basso M, Colusso E, Tancon M, *et al.*: **Hydrophobic hybrid silica sol-gel coating on aluminium: Stability evaluation during saturated vapour condensation.** *J Non Cryst Solids X.* 2023; **17**: 100143.
Publisher Full Text
15. Del Col D, Parin R, Bisetto A, *et al.*: **Film condensation of steam flowing on a hydrophobic surface.** *Int J Heat Mass Transf.* 2017; **107**: 307–318.
Publisher Full Text
16. **GeoHex**.
Reference Source
17. Snorrason DI, Adalsteinsson SM, Tryggvason TK, *et al.*: **Structural stability and oxidation resistance of amorphous TaSi-based ternary alloy coatings.** *J Non Cryst Solids X.* 2023; **18**: 100183.
Publisher Full Text
18. Draper NR, Smith H: ***Applied regression analysis***. John Wiley & Sons. 1981.
19. Martelo D, Schneider G, Bhamji I, *et al.*: **Investigation of the effects surface alteration via coatings on the condensation heat transfer and wettability.** *Zenodo,* [Data set]. 2023.
20. Soebbing JB, Skabo RR, Michel HE, *et al.*: **Rehabilitating water and wastewater treatment plants.** *Journal of Protective Coatings & Linings.* 1996; **13**(5): 54–64.
Reference Source
21. Law KY, Zhao H: **Surface wetting: characterization, contact angle, and fundamentals.** Basel, Switzerland: Springer International Publishing, 2016.
Publisher Full Text
22. Chae HB, Schmidt JW, Moldover MR: **Surface tension of refrigerants R123 and R134a.** *J Chem Eng Data.* 1990; **35**(1): 6–8.
Publisher Full Text
23. Torrealba EJ: **Droplet repellency of microfabricated surfaces in saturated environments.** Master of Science in Mechanical Engineering, University of Illinois at Urbana-Champaign, 2013.
Reference Source
24. Wojdyla A, *et al.*: **D3.2 Superhydrophobic, superoleophobic surface with CuO nanostructures for condensing heat transfer.** GeoHex project. 2021.

Open Peer Review

Current Peer Review Status: ? ? ?

Version 1

Reviewer Report 24 July 2024

https://doi.org/10.21956/openreseurope.18155.r40659

© **2024 Sett S.** This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

?

Soumyadip Sett
Indian Institute of Technology Gandhinagar, Palaj, India

The aim of this research is to improve heat transfer performance by enabling dropwise condensation on aluminium plates through surface modifications. Multiple techniques are used to achieve various levels of hydrophobicity. Overall, the work is well presented, but some sections need to be addressed for clarity and to improve the quality of the manuscript.

1. Results and Discussion: This section related to heat transfer results needs significant revision. It appears the authors have the necessary data, but the presentation lacks structure and clarity. In contrast, the wettability section is well written. The discussion should include comparisons of heat transfer performance between different surfaces and be more quantitative, emphasizing enhancement gains in terms of percentages or actual numbers.
2. The authors mention fabricating several coatings in the Materials Section, but the condensation heat transfer results are not clearly stated or highlighted for all of them. Instead, the focus is on bare Al surfaces. A table listing the heat flux and heat transfer coefficient (HTC), similar to Table 4 for wettability, would be beneficial. The distinction between horizontal and vertical setups is unclear; subsections could help differentiate these setups.
3. The term "mock-up heat exchanger rig" is misleading. It should be rephrased to "condensation rig" or something similar. Heat exchangers involve specific types and flow parameters, making the current term inappropriate.
4. The authors confidently claim that the coatings will be implemented in commercial heat exchangers. However, much work in terms of durability and scalability needs to be undertaken before the commercial stage. The authors should tone down such strong claims in the conclusions.
5. Can the authors include surface roughness characterization (AFM or profilometry) results? Additionally, discussion on the thickness of the coatings is necessary, even if the coatings are too thin for accurate measurement.
6. The scalability of the magnetron sputtered samples is questionable. The authors claim that the developed coatings will be implemented for geothermal plant heat exchangers. How would such coatings be implemented at such large scale?

7. The quality of figures can be significantly improved.
8. In the Introduction section:

1. "...assessed through the contact angle formed between condensing fluid and surface of material." The definition of contact angle can be refined to include that it is the angle at the three phase contact.
2. The reason why dropwise condensation leads to higher heat transfer compared to filmwise (regeneration of nucleation sites, no film thermal resistance, etc.) might be helpful to the readers as to why dropwise is preferred.
3. There are several recent works focusing on Al surface modifications for enhanced heat transfer through dropwise condensation: (Mendizábal, Johannes Köhler, et al., International Journal of Heat and Mass Transfer 207 (2023): 124012; Li, Longnan, et al., ACS Applied Materials & Interfaces 13.36 (2021): 43489-43504; Parin, Riccardo, et al. Surface and Coatings Technology 348 (2018): 1-12; Ho, Jin Yao, et al., Advanced Science 9.24 (2022): 2104454). The authors should include a section on the recent works particularly for aluminum surfaces.
4. In the Methods section:
5. The authors should mention why the opted for R-134a as the test fluid, considering lower GWP refrigerants are preferred these days
6. The authors should mention the mass flow rate of the cooling water
7. In Figure 1, scale bar in the photograph is missing. Also, with respect to the aspect ratio of the figure, the photograph can be larger.
8. In the silica nanoparticles procedure, the authors mention "... desired amount of TEOS, ...". The authors should specify the amount of each component.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Phase change heat transfer, Thermal management, Surface engineering

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 29 May 2024

https://doi.org/10.21956/openreseurope.18155.r39446

© 2024 Kirubaharan A. This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

?

AM Kamalan Kirubaharan
Department of Coating Process, Alexander Dubck University of Trencin, Slovakia, Trencin, Trencianska, Slovakia

The objective of the research was to enhance the heat transfer performance by modifying the surface of aluminum plates. Two distinct methodologies were employed to achieve varying degrees of hydrophobicity. The initial method involved applying an amorphous metal coating to the aluminum surface, effectively transforming it from hydrophilic to hydrophobic without impacting its surface finish or roughness. The second approach aimed to achieve super-hydrophobicity, or a similar level, by modifying the surface roughness and incorporating materials with low surface energy. The author claims that all the materials exhibited exceptional durability in the mild environment. This work is well executed and nicely written. I have some questions that must be addressed:

1. Particle size analysis – provide particle size distribution graph.
2. Why did the author functionalize silica nanoparticles. Is it for removing agglomeration? How did the authors ensure the functionalization is performed? FTIR data could help.
3. Please write the curing procedure in the experimental section.
4. Why the author prefers amorphous metal coatings.
5. If the substrate temperature is not given during sputtering, what will be the residual stress of the coatings?
6. Provide XRD amorphous data.
7. ASTM D4541 is suitable for flat samples. The author could have performed it using scratch tester.
8. Is it possible to apply amorphous Si:Nd:Zr coating on tubular specimens with a uniform thickness using sputtering. If not the case, why did the authors attempt to study using sputtering process.
9. Where is the evidence for the thickness of the coatings?

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: thin films and coatings

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 07 May 2024

https://doi.org/10.21956/openreseurope.18155.r38950

© 2024 Budakli M. This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

?

Mete Budakli
Ozyegin University, Istanbul, İstanbul, Turkey

Methods: Please correct the following word: *"The wettability and adhesion of the coatings **were** characterized before and..."*
Introduction:

1. Remove the bracket: *"...facilitates condensate removal (typically done for high Reynolds..."*
2. Overall, the introduction is well-written and the major literature review is given, however, the introduction should be extended by using the references given below: [Ref 1,2,3,4,5,6,7]

Method:
The authors should draw a professional process flow chart and indicate each relevant component/devices. Furthermore, a cross-section image of the condensation chamber should be provided in which the measurement locations are highlighted. Additionally, the maximum operating conditions considered for the test section should be listed.

- What would have happened to the wetting occurrence on the subcooled surface, if the cooling liquid (water) was pumped from bottom to top instead pumping the fluid from top

to bottom?
- The authors should give the uncertainties for their measured values.
- What series of aluminium have the authors used in their study? E.g. 6000 or 7000?
- Regarding the surface pre-treatment, the authors should write the concentrations they have used for each chemical material.
- What about calibration of thermocouples and the pressure sensing technique?
- Why the authors did not consider insulation or construction of a temperature-controlled cabinet for the condensation chamber in order to minimize/get rid of ambient temperature effects?
- Please, increase the quality of all Figures.
- At what temperature and pressure were the condensation tests carried for water and diiodomethane?

In order to make a good statement of the coating quality, the authors should provide SEM images for each coated surfaces including EDS and XRD analysis. Furthermore, images of surface wetting captured during the condensation process should be added, too.
Another point is that the authors should also include the Nusselt theory for film-wise condensation as comparison for their results obtained in the experiments.

References

1. Lo C, Chu Y, Yen M, Lu M: Enhancing Condensation Heat Transfer on Three-Dimensional Hybrid Surfaces. *Joule*. 2019; **3** (11): 2806-2823 Publisher Full Text
2. Liu Y, Moevius L, Xu X, Qian T, et al.: Pancake bouncing on superhydrophobic surfaces.*Nat Phys*. 2014; **10** (7): 515-519 PubMed Abstract | Publisher Full Text
3. Wang H, Nguyen Q, Kwon J, Ma H: Condensation and Wetting Behavior on Hybrid Superhydrophobic and Superhydrophilic Copper Surfaces. *Journal of Heat Transfer*. 2020; **142** (4). Publisher Full Text
4. Le Fevre E, Rose J: An experimental study of heat transfer by dropwise condensation. *International Journal of Heat and Mass Transfer*. 1965; **8** (8): 1117-1133 Publisher Full Text
5. ORKAN UÇAR İ: Droplet condensation on polymer surfaces: A review. *TURKISH JOURNAL OF CHEMISTRY*. 2013. Publisher Full Text
6. Ma X, Tao B, Chen J, Xu D, et al.: Dropwise condensation heat transfer of steam on a polytethefluoroethylene film. *Journal of Thermal Science*. 2001; **10** (3): 247-253 Publisher Full Text
7. Neumann A, Abdelmessih A, Hameed A: The role of contact angles and contact angle hysteresis in dropwise condensation heat transfer. *International Journal of Heat and Mass Transfer*. 1978; **21** (7): 947-953 Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Condensation and Boiling heat transfer, liquid cooling technologies, Anti-icing surfaces, Spray cooling, Thermal Energy Storage systems, phase-change materials

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.