Enhanced Hybrid Dry Cooler for Solar Cooling —Self Cleaning Surface Modifications

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Abstract

Due to the increasing use of air conditioning in residential buildings and its associated electric energy consumption, the alternative of using solar thermally driven cooling processes is investigated at Fraunhofer UMSICHT. In this work, the use of hydrophobic, self cleaning surfaces in compact hybrid dry coolers for small capacity solar cooling applications is presented. Hybrid dry coolers are usually operated in dry mode, but if the ambient temperature rises over a minimum ambient air temperature, sprayed with water to maintain the capacity. It is necessary to apply a hydrophobic and self cleaning/easy-to-clean modification to avoid scaling and fouling on the lamellae, because untreated tap water shall be used to limit the operating costs. Different structuring methods and coatings are chosen on the basis of a literature and market research, applied on sample sheets and tested within a stress test, where tap water spraying phases are alternating with dry phases. The surface properties before and after the stressing cycles are determined by advancing and receding angle measurements and optical examination. First results are presented and discussed in this paper.

1. Introduction

Cooling and air conditioning of residential buildings is a growing market due to increasing living standards and increased internal loads (i.e. from office equipment, consumer electronics). Electrical cooling devices are well established, but in order to avoid electricity consumption peaks during summer, the use of solar thermal energy for thermally driven sorption chillers is a good alternative to provide environmental and economical benefits. For example surplus heat from solar heating applications can be used during summer when the availability of solar energy and the need for air conditioning and cooling coincide.

For those systems improved hybrid dry coolers as heat rejection units for small scale heat driven chillers are developed at the Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT within the project “Nanotechnology in Solar Cooling” (supported by E.ON Research Initiative).

If the dry bulb temperature is too high to cover the required chiller process temperatures in dry mode, the hybrid cooler could be sprayed with water. This results in an additional cooling effect by water evaporation. To limit the operating costs and in contrast to wet cooling towers, where different chemicals—like hardness stabilizers, disinfectants or corrosion inhibitors—have to be added to the cooling water, the hybrid dry cooler shall be run with tap water, preferably without any water purification or treatment. The water shall be used up completely without creating airborne aerosols, recirculation or any drip off of excess water to avoid any problems related to legionellae and biological growth that could be an obstacle for the use in the residential building sector.

But if mineral salts or organic materials remain on the heat exchanger surface, due to the usage of non-treated tap water, severe fouling would appear and result in a decrease of heat transfer, increase of the air flow pressure drop, finally block the heat exchanger lamellae and reduce the efficiency significantly. The same would be caused by airborne particles from ambient air, which would adhere to the wet surface and build up scale layers.

Therefore, a modification of the heat exchanger surface is being investigated at Fraunhofer UMSICHT. Using nano- and micro structuring methods and special coatings, hydrophobic surfaces with self cleaning properties are created and characterized. (Note: In this context, self cleaning does mean the cleaning with moving water.)

The main aims of the modifications are:

- to create a hydrophobic surface with self cleaning properties,
- to avoid fouling / scaling, microbiological adhesion, corrosion and
- to achieve stable surface states / good ageing properties.

For good hydrophobic (high contact angle) and self cleaning properties, some aspects are important. Plain surfaces can show high static contact angles up to 120 ° as described in [1]. If higher contact angles shall be realized, a structured surface (possibly double structured / micro structured with nano scaled substructures) could be necessary. Conversely this means that—besides a structured surface—a hydrophobic surface constitution has to be present, so that water cannot penetrate the structures and substructures of the surface. On structured surfaces, dirt or other particles have a very small area to adhere and if water droplets are rolling over these particles, they stick to the droplet's surface and will be removed by the moving water. Since the structures are instable against mechanical loads, plain surfaces can possibly provide a better long-term stability.

Based on these information, different modification methods have been found by a literature and market research.

For example anodic oxidation, polishing, chemical etching, laser ablation or stamping can be used to structure a surface. Hydrophobic layers can be generated using myristic acid or different waxes, SAM forming silanes or monoalkylphosphates, sol-gel coatings and Aerosil® particles. Physical vapour deposition (PVD), chemical vapour deposition (CVD), dip or spray coating and other methods can be used to apply the layers. The different methods can be found in [2-9] for example.

2. Materials and Methods

2.1. Materials and Preparation of Hydrophobic and Self Cleaning Surfaces

For all tests aluminium samples with a size of 5×10 cm were used. These samples were cut out of a coil used for heat exchangers, friendly donated by GEA Küba GmbH.

For a comparison of the properties, six different commercial sol-gel coatings and three other modification methods were applied on aluminium samples.

The different methods are listed below.

• Myristic acid (MS): Structuring by anodic oxidation, myristic acid as coating corresponding to [2]

• n-Decyltriethoxysilane (DT): Mechanical and chemical structuring, DT self assembled monolayer (SAM) formation in compliance to [3]

• Sol-gel coatings: Single component coatings (abbreviated as NT, NW, HT, LO) and two component coatings (abbreviated as WI, NL), mostly based on polysiloxane epoxy resin

• Aerosil® R202 (AA): Sol-gel coating + Aerosil layer (pyrogenic silica treated with polydimethylsiloxane (PDMS), BET surface: 100±20 m^2/g, primary particle size: 14 nm, Evonik Industries AG).

The treatments within the different methods are listed in Table 1. All samples were degreased with acetone and rinsed with DI water before the described steps were performed.

Table 1. Sample treatments.

Method	Pre-Treatment	Structuring	Coating/Layer deposition	Curing
Sol-gel coating	NaOH, HNO_3	–	Sol-gel spray coating	Variable, T = room temperature – 250 °C
Myristic acid	NaOH, HNO_3	Anodic oxidation in H_2SO_4	Melted myristic acid	T = 80 °C
n-Decyltriethoxysilane	–	Mechanical, chemical (etching: $Cu(NO_3)_2$ + HNO_3)	n-Decyltriethoxysilane in ethanol + H_2O	T = 150 °C
Aerosil®	NaOH, HNO_3, Coating (sol-gel, see above)	Spraying with Aerosil dispersion		T = room temperature

2.2. Measurements of Wettability

To investigate the hydrophobicity of the samples' surface, static and dynamic contact angles were measured. The static contact angles (see Fig. 1 a) were determined using a digital microscope (VHX-100, Keyence Corporation) and the corresponding software. On rough surfaces, the apparent contact angle can be different from the actual contact angle (cf. Fig. 1 b) thus the dynamic behaviour (advancing and receding angle) is examined also.

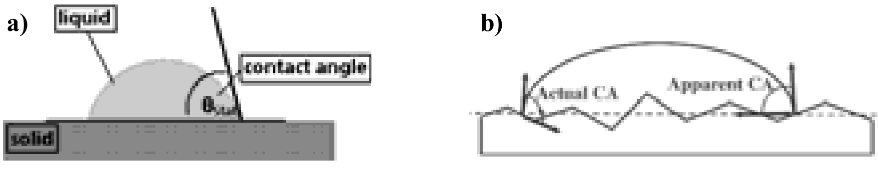

Fig. 1. Schematic figure of a) static contact angle determination, b) influence of roughness [10].

Advancing and receding angles give information about the behaviour of moving water on the surface (e.g. sprayed on or rolling off water) and were determined by tensiometer measurements (DCAT 21, DataPhysics Instruments GmbH) with the dynamic Wilhelmy plate method. The software SCAT 2.4.1.46 calculates the two angles via weight measurements. The angle determinations are shown schematically in Fig. 2 a) and b), an example measurement is displayed in Fig. 1 c).

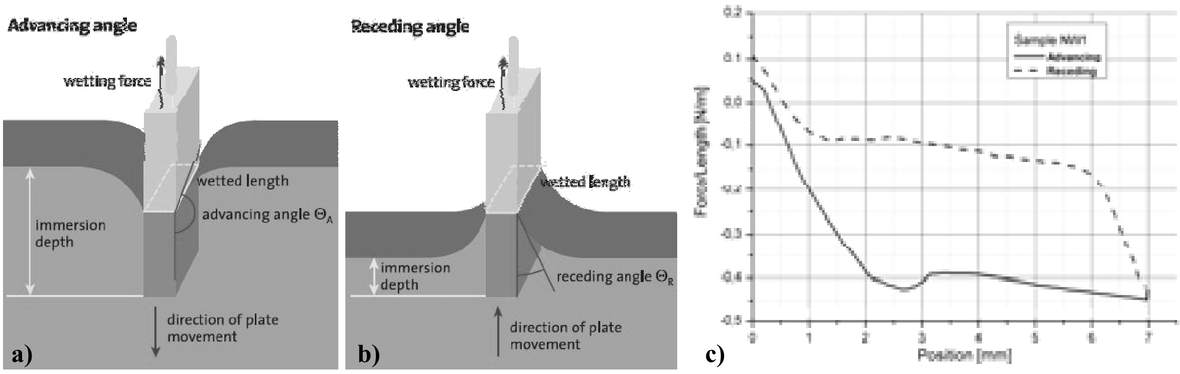

Fig. 2. Schematic figure of a) advancing and b) receding angle determination [11], c) Example of tensiometer measurement.

The calculation is according to (1),

$$\cos\theta = \frac{F_g}{l_w \cdot \sigma}, \tag{1}$$

with the contact angle θ, the liquid's surface tension σ, the wetted length l_w and the total force F_g. F_g is calculated from the buoyancy, the wetting force and the sample's weight.

2.3 Durability Tests

To determine the properties and durability of the generated surfaces, one sample of each applied method was chosen and periodically treated with tap water spray and dried to simulate intensified conditions. After drying, dynamic contact angle measurements were carried out.

3. Results and Discussion

3.1. Contact Angles of Unstressed Samples

The main results for unstressed samples are as follows:

- Modified samples show larger static contact and advancing angles than unmodified samples.
- Structured samples appear to have higher differences between advancing and receding angles.
- The highest contact angles can be realized with structured surfaces.

In Fig. 3 the mean values of static contact angles as well as advancing and receding angles are displayed.

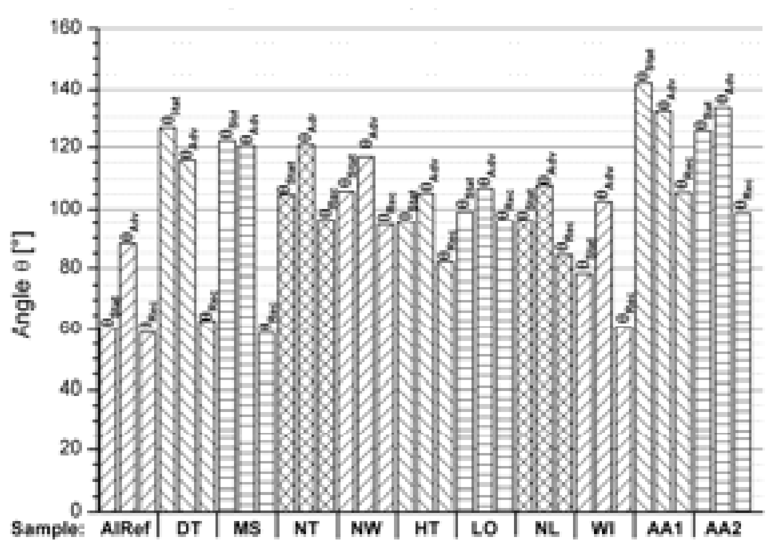

Fig. 3. Mean values of static contact angles (θ_{Stat}), advancing (θ_{Adv}) and receding (θ_{Rec}) angles of all measured samples out of four samples per modification method.

As described above, plain surfaces lead to lower static contact angles than structured, hydrophobic surfaces. This can be verified by the measured static contact angles on plain surfaces that are well below 120 °. Structured surfaces can show contact angles above 120 °. But it is also obvious that the advancing angles of plain surfaces are higher than the static angles. Even if the static contact angles are not that high, these surfaces are nearly non-wettable, as demonstrated in tests with rolling off water droplets. Single water droplets accumulate to big, flat droplets, but the surface stays dry after the water left it. Because of the homogeneous surfaces, these samples have lower hysteresis values (difference between θ_{Adv} and θ_{Rec}) than structured samples.

As an example, an MS modified sample is shown in Fig. 4. This sample has a high hydrophobicity and also good cleaning qualities. In Fig. 4 a) the spherically shaped droplets proof the hydrophobicity. The picked up dirt in Fig. 4 b) reveals the self cleaning properties.

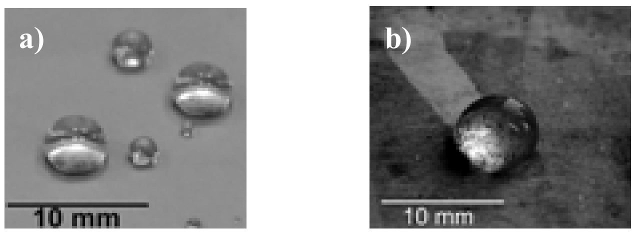

Fig. 4. a) Spherically shaped water droplets and b) picked up dirt by water droplet on MS modified sample.

3.2. Results after Durability Tests

After being sprayed with tap water for 200 h and dried, the sample properties were investigated using tensiometer measurements and optical examination. Some of the samples exhibit heavy corrosion attacks, aluminium hydroxide is visible and pitting corrosion does occur. Other samples show no corrosion attack or have corrosion products on the edges only. The advancing and receding angles are decreasing (cf. Fig. 5 a) and b). Advancing angles on dry samples are higher than on wetted samples and also higher than receding angles.

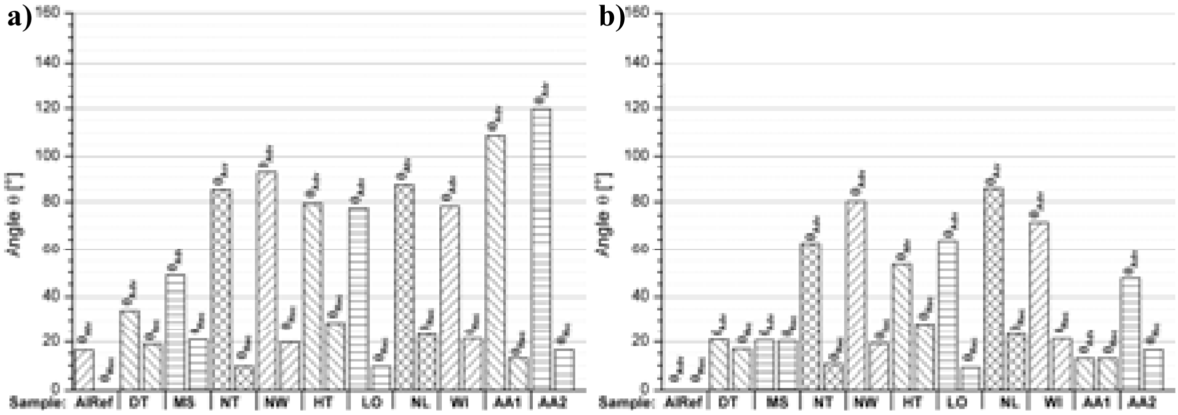

Fig. 5. Advancing and receding angles of a) dry and b) wetted samples after 200 h of spraying with tap water.

Receding and advancing angles of wetted structured surfaces show similar values (except for AA2). During the first immersion, water is displaced by the structured sample sheets, causing high contact angles, because the water does not penetrate the structures in the beginning (AA1, AA2). After immersion, the water penetrates the structures, due to the loss of hydrophobicity and leads to very small contact angles. On the DT modified sample, hydroxide is formed, so that the contact angles are very low. The sample modified with MS does not show any corrosion attack at all, but the susceptible surface lost its hydrophobicity after 200 h of spraying with tap water.

Plain surfaces are evenly wetted from the first immersion on. Therefore, they have nearly the same advancing angles in dry and in wet state. Differences occur on samples that are subject to corrosion attack. The formed hydrophilic aluminium hydroxide creates areas with a higher solid surface free energy and leads to lower advancing angles on wet surfaces, while the contact angle hysteresis increases.

Surface changes, which are not visible to the naked eye, can be determined using confocal microscopy (µsurf, NanoPhysics GmbH) as shown in Fig. 6 exemplarily. In section b), scaling is visible after spraying with water, while in section a) the intact surface of the MS modified sample is displayed.

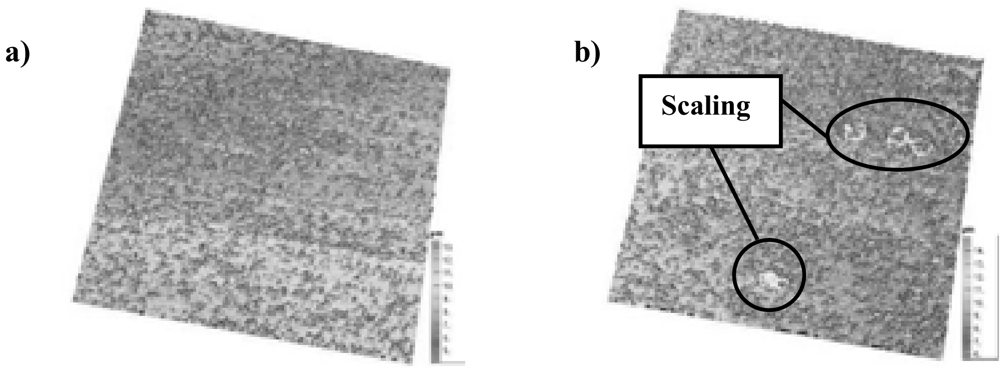

Fig. 6. Surface scan (1000 x), MS modified sample a) before and b) after spraying with water.

5. Conclusions and Outlook

In conclusion, hydrophobic surfaces were successfully generated on aluminium by different structuring and layer deposition or coating methods. Some surfaces show a better behaviour in the long term tap water spray test, like the sol gel coated samples NW and NL. DT and MS modified samples, where the surfaces where structured before layer deposition, lost their hydrophobic properties completely.
The methods with the better long term stabilities will be tested again. Furthermore, other coatings and methods have to be applied and investigated. In the future, the search for alternative methods will be proceeded.

Combinations of structuring and commercial coatings and/or the addition of additives/corrosion inhibitors to a commercial coating are conceivable. Additionally another structuring method (laser ablation structuring) can be investigated later on, as a new laser system is installed at Fraunhofer UMSICHT. Another possibility is the application of PVD or CVD techniques for structuring and layer deposition also.

To acquire information on the surface structure, roughness and changes after the durability tests, more surfaces are investigated using confocal microscopy; partial damages and scaling can be detected.

The investigations will be continued, including the modification of heat exchanger lamellae. In practical tests, the resulting heat exchanger will be examined for its properties like performance, heat transfer and the needed amount of sprayed on water.

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