Dropwise condensation on superhydrophobic nanostructured surfaces: literature review and experimental analysis

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Abstract. It is well established that the dropwise condensation (DWC) mode can lead up to significant enhancement in heat transfer coefficients as compared to the filmwise mode (FWC). Typically, hydrophobic surfaces are expected to promote DWC, while hydrophilic ones induce FWC. To this end, superhydrophobic surfaces, where a combination of low surface energy and surface texturing is used to enhance the hydrophobicity, have recently been proposed as a promising approach to promote dropwise condensation. An attractive feature of using superhydrophobic surfaces is to facilitate easy roll-off of the droplets as they form during condensation, thus leading to a significant improvement in the heat transfer associated with the condensation process.
High droplet mobility can be obtained acting on the surface chemistry, decreasing the surface energy, and on the surface structure, obtaining a micro- or nano- superficial roughness. The first part of this paper will present a literature review of the most relevant works about DWC on superhydrophobic nanotextured substrates, with particular attention on the fabrication processes. In the second part, experimental data about DWC on superhydrophobic nanotextured samples will be analyzed. Particular attention will be paid to the effect of vapour velocity on the heat transfer. Results clearly highlight the excellent potential of nanostructured surfaces for application in flow condensation applications. However, they highlight the need to perform flow condensation experiments at realistic high temperature and saturation conditions in order to evaluate the efficacy of superhydrophobic surfaces for practically relevant pure vapor condensation applications.

1. Introduction
Vapor condensation is an important phenomenon in nature with direct applications to many fields ranging from the chemical to the power industries. Thus, enhancing thermal transport during condensation is a subject which has received a lot of interest in the literature, being at the center of numerous scientific investigations.

It is well established that the dropwise condensation (DWC) mode can lead up to several hundred percent enhancement in heat transfer coefficients as compared to filmwise condensation (FWC), as firstly underlined by Schmidt et al. [1], who recognized that during DWC heat transfer coefficients are 5 – 7 times higher than those obtained with filmwise mode, and more recently by Rose [2]. The main

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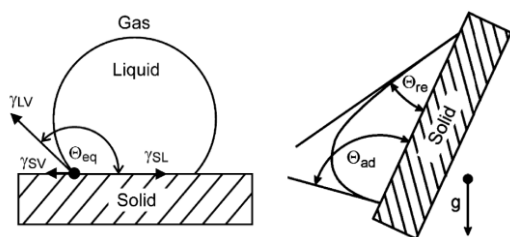* To whom any correspondence should be addressed.

mechanism responsible for heat transfer increase in dropwise condensation over filmwise one is related to droplets mobility. The sweeping and renewal mechanism present in the droplet growth process during DWC directly leads to an augment of both heat and mass transfer coefficients. Moreover, the absence of a liquid layer adjacent to the wall avoids the introduction of an additional thermal resistance which adversely affects the thermal and mass transport.
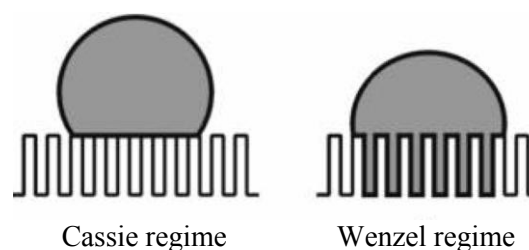
DWC occurs on surfaces which are not strongly wetted by the liquid, thus avoiding drops spreading out over them. Surfaces with strong hydrophobicity are believed to allow effective DWC, due to the promotion of the drop movement and departure and consequently accelerating surface renewal, allowing small drops to form. Thus, water-repellent (hydrophobic) surfaces should promote dropwise condensation, while water-attracted (hydrophilic) ones should promote FWC [3].

To this end, superhydrophobic surfaces, where a combination of low surface energy and surface texturing is used to enhance the water-repellency, have recently been proposed as a promising approach to promote dropwise condensation [4-7]. Surface wettability is defined by the contact angles of a drop sitting over it. As it can be seen in figure 1, taken from [8], for a static drop the equilibrium contact angle Θ_{q} is taken as a reference, while for moving drops the advancing and receding contact angles Θ_{d} and Θ_{e} are considered. The difference among the last two gives the contact angle hysteresis. Superhydrophobic surfaces present high contact angles, greater than 150°, and low water contact angle hysteresis. These surfaces can be produced by combining two factors: hierarchical roughness scale and hydrophobic coating. These two elements allow water droplets over the surface to easily roll-off, thus improving heat transfer associated with the condensation process [9-13].

When referring to humid air condensing over a superhydrophobic micro-/nano- rough surface, droplets mobility can be promoted by air trapped between the droplets and the texture of the surface, i.e. by promoting the so-called Cassie state of a droplet on a superhydrophobic surface [14], schematically shown in figure 2 [10]. On the contrary, during condensation of a pure vapor it is assumed that the vapor trapped between surface textures condenses in contact with the cold wall. If steam condenses both on the top and between surface textures, droplets sitting on the top of the posts in a Cassie state can coalescence with water between the textures transiting to a Wenzel state, which is characterized by drops penetrating the asperities of the rough surface, as it can be seen in figure 2 [10]. Water droplets which are in a Wenzel wetting regime are strongly pinned on the superhydrophobic substrate, thus they present high adhesion and low mobility. The increase in droplet adhesion is strongly associated with an increase in the droplet contact angle hysteresis. The Wenzel state with its high hysteresis is especially favored by a reduction in the liquid surface tension [15-16] and an increase in the ambient humidity [17-18].

Figure 1. Static and dynamic contact angles over a surface [8].

Figure 2. Wetting regimes over a superhydrophobic rough surface [10].

Over the past few decades, considerable attention has been paid toward the development of suitable DWC promoters. The method most employed so far to produce hydrophobic surfaces is to coat the metallic substrate with a thin layer of a material with small surface energy, such as organic substances, polymers, and noble metals. In the recent years, thanks to the developments in the material science, new techniques have been discovered which allow constructing superhydrophobic surfaces by mimicking the surface texture of the lotus leaves, such as micromachining, micro-contact-printing,

chemical etching in aqueous solutions and deep radiative ion etching. Nano-engineered superhydrophobic surfaces appear to be a viable and promising solution to promote dropwise condensation.

2. Literature review

In this section a short review of the most relevant works about DWC on superhydrophobic surfaces is presented.

Sarkar et al. [19] demonstrated superhydrophobicity on micropatterned aluminum surfaces obtained by chemical etching with hydrochloric acid (HCl). After the etching treatment the surfaces were coated with an ultrathin rf-sputtered Teflon film using Ar plasma in an inductively coupled plasma reactor. The optimum etching time to obtain high superhydrophobic properties on the surface was 2.5 minutes (contact angle up to 164° and contact angle hysteresis down to 2.5°). More recently, the same authors [20] investigated wetting characteristics of micro-nanorough substrates of aluminum chemically etched using dilute HCl, comparing them by depositing hydrocarbon and fluorinated-hydrocarbon coatings via plasma enhanced chemical vapor deposition. The authors found a contact angle equal to 135° for the hydrocarbon coated surface, and equal to 165° for the fluorinated-hydrocarbon coated one.

A particular treatment to vary the surface wettability is the one proposed in [21], where the creation of superhydrophobic properties on aluminum alloy surfaces treated with a simple one-step process is reported. This process incorporatres low surface energy compounds in the solution used for the creation of surface micro-roughness. Clean Al coupons were superhydrophobized by dipping them in beakers containing a mixture of sodium hydroxide (NaOH) and fluoroalkyl-silane (FAS-17) at different FAS-17 to NaOH ratios. The authors verified that the formation of a rough microstructured surface, in combination with a modified surface chemistry, leads to the creation of superhydrophobic properties. In particular with 1M NaOH and 400 mM FAS-17 the authors obtained a contact angle equal to 162° and a contact angle hysteresis equal to 4°. An alternative approach is the one proposed in [22], where a method for fabricating superhydrophobic aluminum surfaces by chemical etching without hydrophobic treatment is developed. Washed aluminum substrates were treated with 1 mol L^{-1} NaOH aqueous solution for 10 min at room temperature, and immersed in a mixed acid solution of hydrochloric (36 wt%) and acetic acids (CH_3COOH - 99.6 wt%) at the desired ratio of volumes for the desired time. The authors found that water contact angle increases with increasing etching time, until a critical value equal to 5 min, and with increasing acetic acid concentration, until a critical value equal to 1mL.

An innovative method to render aluminum substrates superhydrophobic was proposed in [23]. The authors treated the samples by consecutive immersion in boiling water, to roughen them, and Teflon sputtering, to create the hydrophobic coat. To achieve different roughness levels, the duration of the boiling process was varied. They demonstrated that high superhydrophobic properties (contact angle equal to 164° and contact angle hysteresis equal to 4°) can be obtained after 5 minutes immersion in boiling water.

Dietz et al. [6] reported a study of the dynamic condensation on a superhydrophobic sample characterized by cupric hydroxide ($Cu(OH)_2$) nanostructures coated with 1-hexadecanethiol. The $Cu(OH)_2$ nanostructures were fabricated by sputtering 6 micrometers of copper on a silicon substrate. The substrate was then immersed for 30 minutes in a 50 mL solution of 2.5 M sodium hydroxide (50% weight by weight) and 0.09 M of ammonium persulfate previously stirred for 15 hours. Thus, the $Cu(OH)_2$ structures self-assembled. Next, 30 nm of gold was sputtered on the $Cu(OH)_2$ structures followed by a 1 s immersion in 1-hexadecanethiol to reduce the surface energy. Droplet departure frequency was investigated on the superhydrophobic surface and on a nonstructered hydrophobic surface, finding that the droplets tend to depart the textured surface at reduced diameter. Since droplets with diameter less than 10 μm provide the most significant contribution to the heat transfer during dropwise condensation and the formation of new droplets occurs only once large drops have departed from the surface, the authors concluded that the larger surface renewal frequency of the superhydrophobic surface leads to an increase in the heat transfer coefficient.

In [14] wetting modes of water droplets on a microtextured superhydrophobic surface are analyzed. Microtextures were created by ultraviolet microreplication against a nikel master structure. The authors showed that an irreversible transition from the Cassie to the Wenzel wetting regime can be observed if steam condenses inside the surface texture or if DWC is promoted at high external pressure. The authors underlined that if textures are filled with water the surface dramatically losses his water-repellent properties, thus transition between the two regimes should be properly avoided by accurately designing the surface structure.

Lan at al. [24] investigated DWC on a mirror-polished (SAM-2) and a nanostructured (SAM-1) copper substrate prepared with Self-Assembled Monolayers (SAM) coatings on n-octadecyl mercaptan. SAM-1 surface was first immersed in a 30% hydrogen peroxide (H_2O_2) solution for 3.5 h, during which an oxide layer formed on the copper substrate. Then it was immersed in a 2.5 mmol L^{-1} solution of n-octadecyl mercaptan in ethanol for 1 h. Thus, a SAM film of n-octadecylmercaptan formed on the surface. SAM-2 was similarly prepared without oxidation and etching process in H_2O_2 solution. Figure 3 shows the trends of Lan et al. [24] heat transfer data, comparing them against values predicted with the Nusselt theory for filmwise condensation. The authors found that both SAM-1 and SAM-2 surfaces increase heat transfer with respect to the predicted values for FWC, however, although SAM-1 presents better superhydrophobic performances than SAM-2 (i.e. higher contact angles), the authors reported underperformances of the superhydrophobic oxidized surface as compared to the mirror polished one. The nanostructured substrate does not improve DWC heat transfer performance as expected by the higher contact angle, because during pure steam condensation process condensate fills the cavities of SAM-1 surface, thus implying that the DWC takes place on a composite solid-condensate-liquid surface, compromising SAM-1 performances. Consequently, the DWC heat-transfer coefficients of SAM-1 surface are lower than those of SAM-2.
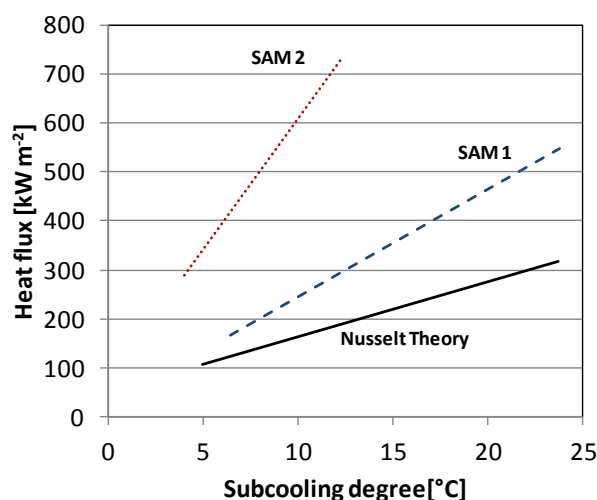

Figure 3. Heat flux trends from [24].

Chen et al. [4] analyzed continuous DWC on a two-tier roughness superhydrophobic surface characterized by carbon nanotubes (CNTs) deposited on micromachined posts, mimicking the structure of the lotus leaves. Squarely positioned pillars were formed by deep reactive ion etching on a Si surface, which was then coated with a thin layer of chromium (100 nm) and then nickel (20 nm) as catalyst, before CNTs were grown by plasma enhanced chemical vapor deposition. The substrate was finally hydrophobicized either by a 10 nm layer of parylene C coating or by a 10 nm layer of gold coated with a monolayer of 1-hexadecanethiol. Comparing experimental results obtained on the two-tier surface with those obtained on a one-tier microtextured one, the authors found increased wetting-repellency performances. In [25] an analysis of a two-tier superhydrophobic surface (similar to the one presented in [4]) is performed. The authors found that during pure vapor condensation process a thick condensate film was formed on the textured surface, dramatically decreasing water mobility.

Autonomous removal of condensate drops on a two-tier roughness superhydrophobic surface (similar to the one proposed in [4]) is reported in [5]. Comparing experimental results obtained during DWC on a horizontally oriented hydrophobic substrate with those obtained in the superhydrophobic one the authors found that, while on the former condensate drops continued to grow and to accumulate, on the second droplets were autonomously removed without the action of any external force. The authors found that self-propelled jumping motion, at a speed as high as 1 m s^{-1}, of condensate drops can be obtained with DWC on superhydrophobic surfaces, leading to autonomous removal of dropwise condensate which has the potential to enhance condensation heat transfer (because of increased droplets mobility).

Varanasi et al. [12] attempted to spatially control heterogeneous nucleation of water by modifying the local intrinsic wettability of a surface. They prepared a textured surface consisting of an array of hydrophobic posts with hydrophilic tops. The hydrophilic regions were made up of the native oxide on a Si wafer, while the hydrophobic ones were modified with fluorosilane. Textures were fabricated via micro contact printing using a prefabricated stamp. The authors demonstrated that nucleation and subsequent growth of droplets occurs preferentially on the hydrophilic post tops of the hybrid surface when compared to the random nucleation of droplets on an identically textured superhydrophobic surface with uniform wettability.

Ko et al. [26] fabricated carbon fibers (CFs) network surfaces with high aspect-ratio nanostructures having superhydrophobic and water-repellent properties. To fabricate superhydrophobic nanostructured surfaces, oxygen plasma etching and coating with hydrophobic material were applied to CFs made of carbonized polyacrylonitrile supported by carbon patches that are mainly composed of carbon powder. Oxygen plasma etching was performed to form the nanostructures on the CFs, and hydrophobic material coating was accomplished with radiofrequency plasma-enhanced chemical vapor deposition system. Aspect ratios were controlled by the oxygen plasma treatment duration. The authors found that, on the superhydrophobic CFs networks with high aspect-ratio nanostructures, a nucleated droplet can maintain its spherical shape and has difficulty to merge with other drops that nucleate in the structure spaces. This phenomena decreases the possibility of transition from the Cassie to Wenzel regime under super-saturated vapor conditions. Thus, during pure steam dropwise condensation on high aspect-ratio surfaces, droplets maintain their high mobility and heat transfer performances are not decreased. This work underlines that micro-nano hierarchical (multiscale) roughness is a key structural factor for sustaining condensed drops in a Cassie state on a superhydrophobic surface during pure steam condensation.

Similarly, in [27] DWC on a multiscale nanograssed micropyramid architecture surface is analyzed. It allows to have global superhydrophobicity as well as locally wettable nucleation sites. Nanograssed micropyramid arrays were fabricated using a combined anisotropic wet-etching and deep reactive ion etching (DRIE) process. After fabricating silicon pyramid microstructures by tetramethylammonium hydroxide etching, the authors performed a modified DRIE process for nanograss coating. Vertically-aligned uniform nanopillar arrays (i.e. nanograss) can be produced by regulating the alternating etching and passivation cycles. To generate relatively smooth patches into the nanograss coating, the authors intentionally over-etched the nanopillar tops in each etching cycle so as to reduce the height of the nanopillars. As a result, the vertical walls underneath the base of the micropyramids were exposed in smooth morphology while the inclined sidewalls and the spaces between the micropyramids were uniformly covered by nanograss. The presence of wettable patches facilitates drop growth and preferential coalescence whereas the global superhydrophobicity promotes spontaneous drop departure without pinning to the substrate. Moreover, synergistic co-operation between the hierarchical roughness structures contributes directly to a continuous process of nucleation, coalescence, departure, and re-nucleation, enabling sustained dropwise condensation over prolonged periods. The authors showed that by harnessing heterogeneous wettability and hierarchical roughness features in multiscale structures, it is possible to enhance both drop nucleation and drop departure on a condensing surface.

A new approach was shown in [28], where the authors demonstrated that pinning of condensate droplets can be drastically reduced by designing hierarchical micro-nanoscale texture on a surface and by impregnating it with an appropriate lubricant, immiscible with the condensed liquid. The

condensing surfaces were well-defined cubical microposts of silicon fabricated by standard photolithography, hydrophobized by a low-energy silane coated over them using solution based deposition. Two lubricants, a fluorinated oil and a ionic liquid, were impregnated into the textured surfaces by dipping them into a bath of lubricant and then withdrawing at controlled rates using a dip coater. The authors demonstrated that, carefully selecting an immiscible liquid with desirable surface energy and spreading coefficient with respect to water, condensation of water droplets on lubricant-impregnated nanotextured surfaces occurs with enhanced droplet mobility compared to non-impregnated superhydrophobic surfaces. Increased mobility is related to condensed droplets floating on the lubricant with minimal pinning to the surface.

With reference to new coating materials, recently Azimi et al. [29] investigated rare-earth oxides (REOs) ceramics, demonstrating that these promote dropwise condensation, repel impinging water droplets and sustain hydrophobicity even after exposure to harsh environments. The authors tested these materials through condensation experiments, exposing smooth silicon wafers sputtered with a thin layer of REOs to saturated steam. Their experiments showed that the REOs are sufficiently hydrophobic to promote dropwise condensation. The robustness of REOs hydrophobicity was positively demonstrated subjecting these coats to a high temperature environment (1000°C) as well as abrasive wear, measuring water contact angles before and after exposure.

Ma et al. [30] investigated steam DWC heat transfer characteristics in the presence of NCGs on a superhydrophobic nanostructured surface. A roughness-induced superhydrophobic vertical surface was prepared with n-octadecyl mercaptan SAM. The authors demonstrated that NCGs can be trapped in the cavities of the nanostructured surface by the condensate droplets (the more the higher is NCGs concentration), this way leading to a transition from Wenzel to Cassie wetting modes. Thus, the superhydrophobicity of the nanostructured surface can be sustained and enhanced during steam condensation in the presence of NCGs, especially at high concentration.

Yin et al. [31] comparatively investigated the effect of environmental factors on superhydrophobic behaviors of surfaces with different low-surface-energy coatings under controllable condensation conditions. Aluminum substrates were treated through a chemical etching process by immersing them in a mixed acid solution of HF, HCl and deionized water for different times, to construct textured morphology. Then, the rough surfaces were treated with fluoro-polymer (PFO), palmitic acid (PA) and RTV (room temperature vulcanization) silicon rubber to obtain superhydrophobic samples. Analyzing PFO-treated surfaces etched for different times the authors saw that, although they were all superhydrophobic after increasing the reaction time over 5 s, the highest contact angle (162°) was obtained on the surface etched for 15 s (S15). Focusing on S15 surface treated with the three different coats it has been shown that PFO-coated one was better both in static and dynamic angles than the others. The authors evaluated influences of surface subcooling degree and relative humidity (RH) on contact and sliding angles for the three S15 surfaces during condensation tests, comparing the results also with those obtained with smooth-coated substrates. Under high RH (>60%), contact angles decrease as well as sliding angles increase, indicating an increased wettability of all superhydrophobic surfaces due to the incremental amount of condensed water at low surface temperatures. However, PFO and PA coated surfaces showed good condensation resistance because of rolling drops even at the lower surface temperatures under RH of 90%. Moreover, the authors found that superhydrophobic behaviors of all surfaces were well resumed after evaporation of condensed water.

High temperature saturated vapor flow condensation tests on superhydrophobic nanotextured copper surfaces presented by Torresin et al. [32] show that condensing drops form and penetrate into the surface texture and attain a Wenzel state, but the vapor shear-induced droplets roll-off compensates for the reduced drops mobility and enhances the overall thermal transport. These results underlined the potential of nanostructured surface for application in flow condensation conditions. This work was aimed at showing the effect of vapour flow during pure vapour condensation.

3. Experimental analysis of flow condensation
In this paper the scalable wet-chemical technique used by Torresin et al. [32] to nanotexture copper surfaces, followed by surface functionalization to render them superhydrophobic, is presented in

detail. Flow condensation tests performed by the authors to experimentally analyze DWC on the treated samples are investigated.

3.1. Superhydrophobic sample preparation

The two-step method herein shown to modify copper surfaces wettability is very simple, requires less than two hours and can be performed at ambient conditions without special equipment.

Before starting the surface treatments each copper sample is mechanically polished and ultrasonically cleaned in ethanol (99% Solvent grade) and Millipore DI water for 5 min each.

The first step of the treatment consists in dipping the polished copper surface in a mixture solution of 2.5 M L^{-1} NaOH and 0.1 M L^{-1} $(NH_4)S_2O_8$ for 12 min. During the entire immersion process the mixture was continuosly stirred. At the end of the process the sample is fully rinsed with deionized water and dried in a nitrogen stream. The first step leads to the formation of wire-like nanostructures on the surface.

In the second step, the modified copper substrate is immersed, at room temperature, in an ethanol solution of 1 mM L^{-1} 1H,1H,2H,2H-persluorodecanethiol (molecular formula $CF_3(CF_2)_7CH_2CH_2SH$) for 30 min followed by washing in ethanol for one hour. With this step, surface energy change was imparted.

The untreated polished surface was hydrophilic, with a water contact angle equal to 86±2°. After the two-step process the surface presents a contact angle of 159±2° and a sliding angle lower than 2° [32].
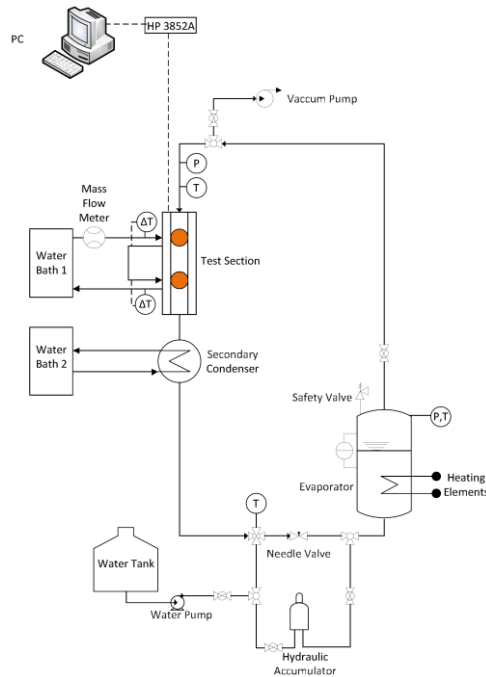
3.2. Test apparatus

A thermosyphon two-phase test rig has been developed to study steam condensation heat transfer. A schematic of the test loop is reported in figure 4, taken from [32].

Steam is generated in a stainless steel cylindrical boiler and directed by a stainless steel insulated pipe into the test section, which consists of a Teflon minichannel (D_h = 3.6 mm) fitted with test surfaces of two cylindrical copper specimens (D = 20 mm), over which condensation occurs. The copper specimens are cooled on the backside. After the test section, the remaining vapor and the condensed liquid pass through a secondary condenser, which completes the condensation process, and are sent back to the evaporator through a gravity drain.

Particular care was taken to avoid NCGs from entering into the test rig. Before filling the system with deionized water, air in the test rig was pumped out using a vacuum pump. A hydraulic accumulator was used to adjust the operative pressure and to maintain the flow loop in overpressure as compared to external ambient, thus avoiding any entry of non condensable gases.

3.3. Test section

A detailed description of the test section, shown in figure 5, is given in [32]. It mainly consists of a rectangular shape minichannel grooved into a Teflon block and covered with a glass plate to allow direct visualization of the process. The Teflon block presents two holes where the copper cylindrical samples are accommodated, with the top surface aligned with the bottom of the minichannel. On the back side each specimen is in contact with a water cooling system, described in [32].

Figure 4. Schematic diagram of the experimental two-phase test loop.

Figure 5. Picture of the test section.

Each cylindrical element is fitted with five T-type thermocouples in holes precisely drilled into the samples. From the acquired temperature profiles in the copper cylinder it was possible to evaluate the surface temperature T_{wall} , the heat flux and the condensation heat transfer coefficient [32]

$$q \ = \ -k \ \frac{dT}{dz} \tag{1}$$

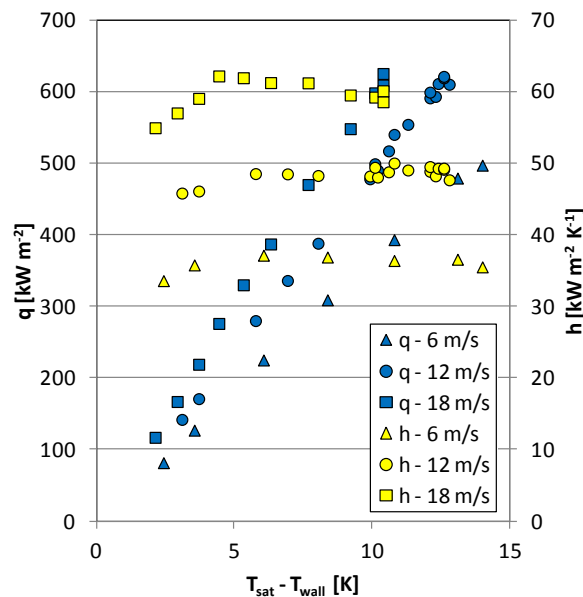$$h \ = \ q \ / \ (T_{sat} - T_{wall}) \tag{2}$$

where k is the thermal conductivity of the sample and z is the axial position. Steam condensation tests have been performed at 1.43 bar, on copper specimens treated with the two-step process as well as on a naturally oxidized polished copper sample (for comparison purposes).

3.4. Experimental results

Figure 6 shows heat flux and heat transfer coefficient data for three different vapor velocities (6, 12 and 18 m s^{-1}). For all the tested velocities steam condenses over the nanostructured superhydrophobic surface in dropwise mode.

The heat flux increases both when increasing the wall subcooling and the flow rate. The vapor steam imposes a drag force on the condensing droplets, which move if it overcomes their capillary adhesion to the substrate. Thus, increasing vapor velocity means reducing droplets departing diameter, thus enhancing thermal performance. Heat transfer coefficient behaves differently with velocity and subcooling: it seems to depend strongly on vapor velocity, while the influence of the subcooling degree is not significant. This highlights the positive influence of vapor flux on the performance of nanostructured superhydrophobic surfaces.

Figure 6. Heat flux (left axis) and heat transfer coefficient (right axis) versus wall subcooling during DWC at different vapor velocities on the superhydrophobic copper sample. Data from [32].

Nanostructured surface was tested for several days to verify its mechanical and chemical robustness. In [32] a comparison between heat fluxes measured over six consecutive working days at $T_{sat} = 110°C$ and $v_{vapor} = 12$ m s^{-1} is shown. Over the first five days no differences were found, and experimental values of heat flux are well reproduced over the whole range of subcooling degrees. Clear differences are noticeable on the last day, when heat fluxes are 35% lower that the formers. This is because condensation mode changes from dropwise to filmwise between the 5th and the 6th working day, because of deterioration of the hydrophobic layer and mechanical degradation of the surface morphology.

Heat fluxes during filmwise condensation over a non-textured sample are compared in [32] against DWC data acquired with the treated surface, showing that for the first five days, at the same operating conditions, the thermal performance of the superhydrophobic sample is better than that of the oxidized one. After six working days however, the treated surface no longer maintains its superhydrophobic properties, and thermal performances of the oxidized copper sample become better.

4. Conclusions

1. A short literature review about dropwise condensation on superhydrophobic micro-/ nanotextured surfaces shows that:

a) Dropwise condensation mode enhances heat transfer performance as compared to filmwise mode, mainly because of high droplets mobility.

b) Superhydrophobic nanotextured surfaces, developed combining hierarchical scale roughness and hydrophobic coating, are a viable solution to promote DWC. Superhydrophobicity (i.e. high contact angles) can be obtained through different surface treatments.

c) If pure steam condenses over a superhydrophobic nanostructured surface, water droplets could pin on the substrate, reducing their mobility. Thus, during pure steam DWC, superhydrophobic nanotextured surfaces can perform worse than non-textured ones. High aspect-ratio substrates, as well as the presence of vapor stream, help to sustain heat transfer performance. On the contrary, during DWC in the presence of non-condensable gases, these are trapped between the surface textures, thus helping to sustain condensate drops mobility.

2. In this paper a simple two-step method to modify copper surface wettability is reported. The treated samples were used to experimentally analyze heat transfer during dropwise condensation of pure steam at 1.43 bar at varying vapor velocity. The present experimental analysis shows that:

a) DWC heat flux increases when increasing both surface subcooling and vapor velocity, while DWC heat transfer coefficient seems to be dependent only on vapor velocity. In fact, vapor velocity helps to maintain high droplets mobility even during DWC of pure steam.

b) Tests performed over different days showed that the treated surface maintains DWC for 5 working days, over which deterioration of the hydrophobic layer and mechanical degradation of the substrate lead to condensation mode change from dropwise to filmwise, with a reduction of heat transfer performances.

c) While maintaining DWC the superhydrophobic surface performs better than a non-textured oxidized one; when transition to FWC occurs, the superhydrophobic surface performs worse.

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