Characterization of droplet distribution on superhydrophobic surfaces during condensation using image analysis

Verteilungseigenschaften von Tröpfchen auf superhydrophoben Flächen während der Kondensation mittels Bildanalyse

N. Fedorova[1,2], M. Moataz[1], R. Boldin[1], A. Zbogar-Rasic[1], V. Jovicic[1,2*], A. Delgado[1,2,3]
[1] Institute of Fluid Mechanics (LSTM) at Friedrich-Alexander University (FAU), Erlangen, Germany
[2] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Germany
[3] German Engineering Development and Research Center LSTME Busan/South Korea

* vojislav.jovicic@fau.de

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Abstract

Increase of the efficiency of condensing heat exchangers can be achieved by promoting the dropwise condensation (DWC). It increases the heat transfer coefficient by up to one order of magnitude compared to the filmwise condensation. For jumping-droplet condensation, which takes place on superhydrophobic surfaces, further increase of heat transfer coefficient (up to 30% higher than in the case of DWC) is reported in the literature. Therefore, understanding the behaviour of droplets during condensation on such surfaces gains on significance.

The goal of this work was to characterize the following distribution characteristics of condensate on the superhydrophobic surfaces as a function of time: number of droplets, surface coverage with the diameter distribution and maximal diameter of droplets. Aluminium alloy ($AlMg_3$) was chosen for substrate, as one of the widely used materials for heat exchangers. The mechanically rolled as-received sample represented a surface with lower roughness (Sa = 5 µm), while the sandpapered sample had almost twice higher roughness (Sa = 12 µm). The superhydrophobicity of these surfaces was achieved by the spray coating based on the fluoroacrylic solution with fluorinated nanoparticles.

Condensation experiments on the coated samples were conducted in the closed chamber, with maintained constant relative humidity. The temperature field along the chamber and excess pressure were measured. The condensation process was recorded for 25 minutes by the HD camera with 180 mm macro lens. Due to the almost perfect spherical shape of droplets and their huge amount on the surface, the evaluation of distribution characteristics was automatized, using the self-developed Matlab® pattern recognition tool.

The coverage of surfaces with condensate droplets was rising in time as expected and was less than 25 % for both samples at the end of the condensation experiment. Most of the droplets had the diameters less than 0.65 mm, indicating a rapid renewal of the cooling surface, which is common for superhydrophobic surfaces. The condensation behaviour was similar on both superhydrophobic-coated samples and independent of the previous mechanical sample treatment. Few experimental images were verified by the ImageJ software and showed a good agreement with the developed Matlab® code.

Introduction

Increase of the efficiency of condensing systems can be achieved by promoting the dropwise condensation (DWC). It increases the heat transfer coefficient by up to one order of magnitude compared to the filmwise condensation (Carey 2008). For jumping-droplet condensation, which takes place on superhydrophobic surfaces, further increase of heat transfer coefficient (up to 30% higher than in the case of DWC) is reported in the literature (Miljkovic 2013). This could be beneficial for the numerous applications where the condensation process takes place, for example, heating, ventilation and air conditioning (HVAC), thermal power plants, thermal diodes, etc. Therefore, understanding the behaviour of droplets during condensation on such surfaces gains on significance.

To characterize the dropwise condensation heat transfer in the laboratory conditions, the common measurements include temperature fields inside the condensation chamber and of the cooling circuit, heat fluxes and heat transfer coefficients. Apart from that, much useful information on the distribution characteristics of condensate droplets, droplets growth and dynamics can be extracted by recording the images and/or videos of the condensation behaviour. In both cases the fast frequency of the recording is required, since the droplets interactions happen fast. However, this results in the large amount of the experimental data to be processed and therefore the automatic extraction of droplets features in time is crucial. Matlab® Image Processing Toolbox provides a set of powerful tools for image processing and analysis that can be used to perform this task in a relatively easy and customizable manner.

The automatization of image processing and analysis for dropwise condensation conditions has been actively used by different researchers. Castillo et al. 2015 investigated the growth of water droplets during dropwise condensation on the hydrophobic surface at different ambient relative humidities in the range from 45 – 70 %. His script enabled to recognize the number and size of droplets in time and to track the single droplet growth in a set of sequential images. Mirafiori et al. 2020 investigated the large drop-size density distribution during dropwise condensation at different operating conditions: four surface coatings and heat flux between 89 and 544 kW/m^2. Chu et al. 2017 investigated the droplet growth characteristics on surfaces with various wettability (hydrophilic, hydrophobic and superhydrophobic) under the air conditions of 20 °C and the relative humidity (RH) 50%, and the surface temperature of 2 °C. On the superhydrophobic surface the droplet size distributions were non-linear and the surface coverage fractions fluctuated randomly with condensation time. The authors attributed this to the frequent self-propelled droplet motion, which disturbs the normal droplet growth rhythm.

The goal of the present work was to characterize the distribution of condensate droplets on the superhydrophobic surfaces, which had different understructure below the coating. The following parameters were under consideration as a function of time: number of droplets, maximal diameter of droplets and surface coverage with the diameter distribution. For automatizing the image processing and evaluation of the condensate distribution characteristics, the Matlab® algorithm was developed.

Materials and Methods

At the beginning, it was necessary to produce and characterize the experimental samples, which was done according to the previously established procedures (Fedorova 2020). Aluminium alloy ($AlMg_3$) was chosen, as one of the widely used materials for heat exchangers. The sample discs were made by mechanical rolling and had the dimensions of 59 mm in diameter and 3 mm thickness. Sandpapering (80 grit) of the substrate aimed to produce the rougher structure. The as-received substrate represented a surface with lower roughness (Sa = 5 µm), while the sandpapered sample had almost twice higher roughness (Sa = 12 µm). The superhydrophobicity of these surfaces was achieved by spraying the commercially available coating, based on the fluoroacrylic solution with fluorinated nanoparticles. Thus, two superhydrophobic samples (with contact angles of 150° and contact angle hysteresis lower than 10°) were prepared:

- Coated substrate, as received (roughness after coating Sa = 23.1 ± 1.9 µm),
- Coated sandpapered (roughness after coating Sa = 29.0 ± 1.2 µm).

The experimental investigations of condensation process on the produced superhydrophobic samples were performed in the setup, schematically presented in Figure 1. Its core was the closed condensation chamber of 3.4 l in volume, filled with the ambient air of 20 ± 3 °C and the relative humidity 53 ± 2 %. The test sample was placed horizontally inside of the chamber and was cooled from the bottom by the circulating cooling water of 4 ± 0.3 °C. Simultaneously, steam was gradually injected inside the reaction chamber. The experiment lasted for approximately 25 minutes and was terminated after the injection of 1 ml of water.

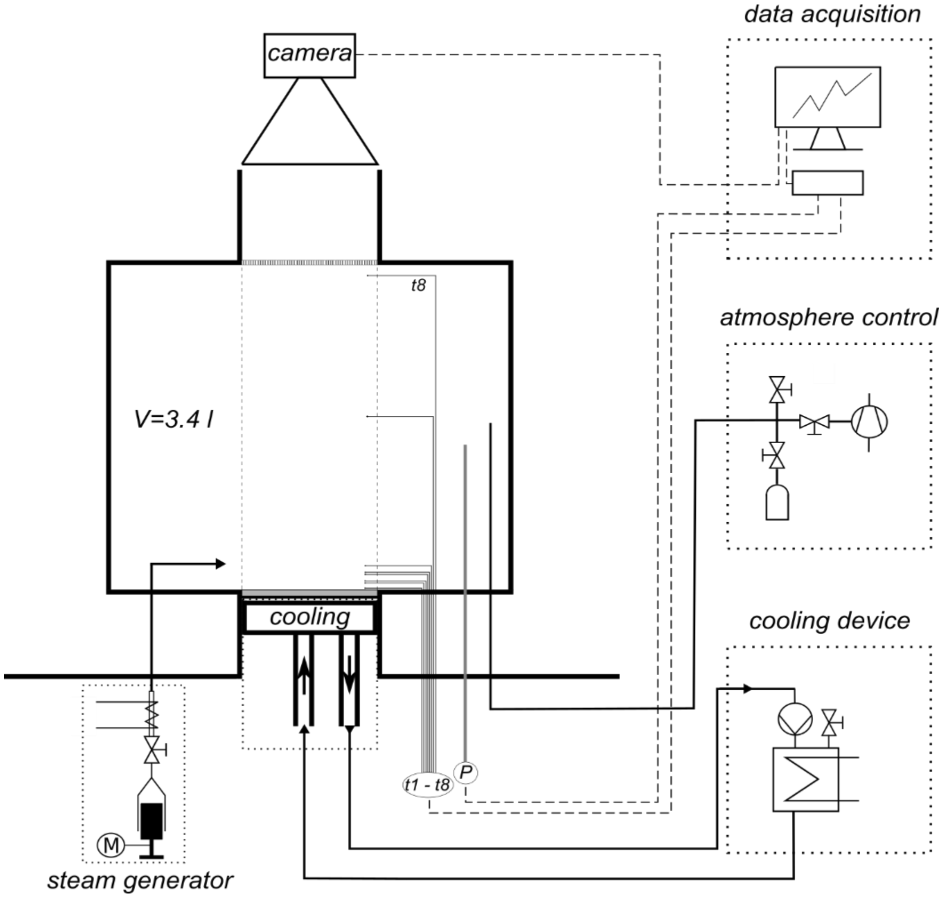

Fig. 1: The schematic of the experimental setup. Solid lines represent the fluid flows, dashed lines represent the data flows

Tab. 1: Position of thermocouples

	Distance to the sample
T1	1 mm
T2	3 mm
T3	5 mm
T4	8 mm
T5	10 mm
T6	13 mm
T7	80 mm
T8	145 mm

The vertical temperature profile along the chamber was measured by eight T-type thermocouples (T1 – T8, positioned at different distances to the sample, specified in Table 1) and the excess pressure was continuously recorded in time. The measured data was collected by the developed Data Acquisition System (DAQ), using the LabVIEW 2017 software. The condensation process on the sample was visually recorded for around 25 minutes from the top through the observation window, using the HD camera. The camera was combined with the 180 mm F2.8 macro lens with the fixed focal length of 180 mm. In order to provide the immobility of the experimental setup and prevent vibrations that could disturb the droplets behaviour, the photographing was performed remotely by the open source software digiCamControl (Version 2.1.0.0) with the frequency of 1 picture per 3 seconds.

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In the end, the experimental photos of condensation process on the test samples were analyzed in regards to the distribution characteristics of condensate droplets. Due to the spherical shape of droplets and their huge amount on the surface, the analysis was automatized, using the self-developed code written on Matlab® - R2018a.

Using the built-in functions of the Matlab® Image Processing Toolbox and adjusting them to our specific case, an image processing algorithm was developed to segment droplets and to analyze the droplet characteristics evolution during dropwise condensation. The image preprocessing steps are presented in Figure 2. After reading the images in Matlab® (function “imread”), they were cropped to the considered area of 15 x 15 mm. This allowed to focus the analysis within the same central part of each sample and to avoid the “edge effects”, which commonly happen at the samples’ edges distorting the droplets shapes and are therefore not representative. Images were then converted to the grayscale (function “rgb2gray”) and their contrast was adjusted (function “imadjust”), so that the enhanced clarity of the droplets was achieved with respect to the background before converting images to binary (function “im2bw”). The threshold level used in the binarization process was 0.6, which for our case maximized the removal of the background pixels (converting them to black) and minimized the loss of the droplets pixels (converting them to white). The black pixels found inside the droplets contours caused by the light reflection on the droplet surface were filled with white pixels (function “imfill”). The algorithm enabled the detection of droplets with diameters of 0.15 mm, while everything below was considered as noise and removed to increase the accuracy (function “bwareaopen”). Thus, the remaining droplets were detected on the sample (function “imfindcircles”).

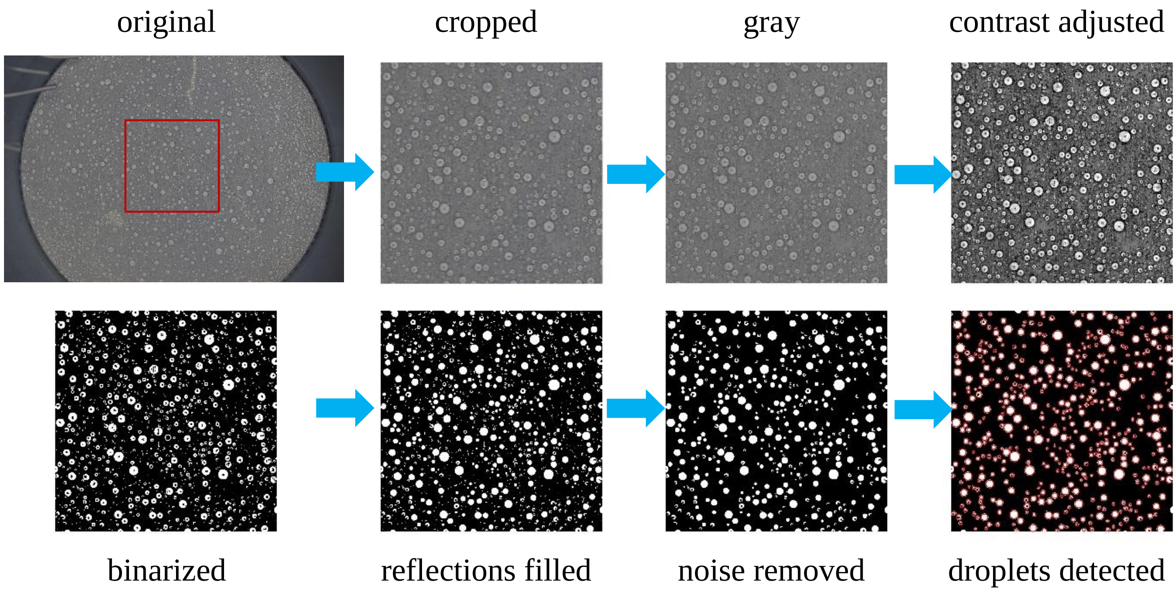

Fig. 2: Algorithm of droplets identification

The code was further developed to enable the definition of the following parameters: total number of condensate droplets, maximal diameter of droplets on the sample and surface coverage with the diameter distribution. The surface coverage was found as the ratio of the projected surface area covered by the droplets over the considered sample’s area. In this way, the set of all experimental images for each sample was automatically processed and sequentially evaluated, to provide the data for characterization of the condensate droplets’ distribution on the superhydrophobic samples in time. The verification of the developed code was done selectively for a few images of each sample with the help of the open source image processing program ImageJ.

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Results and Discussion

The results of image analysis done by the developed Matlab® algorithm showed that the total number of condensate droplets in time varied from around 350 to 550 on both superhydrophobic-coated samples, as presented in Figure 3. The trend was only slightly increasing in case of the coated substrate, as the condensation propagated. In general, the trend stayed rather steady over the whole duration of the condensation experiment (25 minutes). The reason for this was the out-of-plane jumping of condensate droplets upon coalescence, which was reported as the condensate removal mechanism on the horizontally-oriented superhydrophobic surfaces (Boreyko 2009).

Shown in Figure 3, the maximal droplet diameter represents the biggest droplet detected on the surface at each moment of time. Its value was similar on both coated samples and was slightly growing in time from around 0.7 mm to 1.2 mm, as more steam was introduced inside the chamber and in the absence of the gravitational condensate removal on the horizontally-oriented surface. The extreme diameter value of 1.6 mm on the coated substrate is attributed to the individual droplet, that failed to jump and grew so big. This case signified, that the maximal droplet diameter should be carefully considered and preferably complemented with the information on the droplets percentage having the respective diameter, in order to provide the representative results on the condensate distribution.

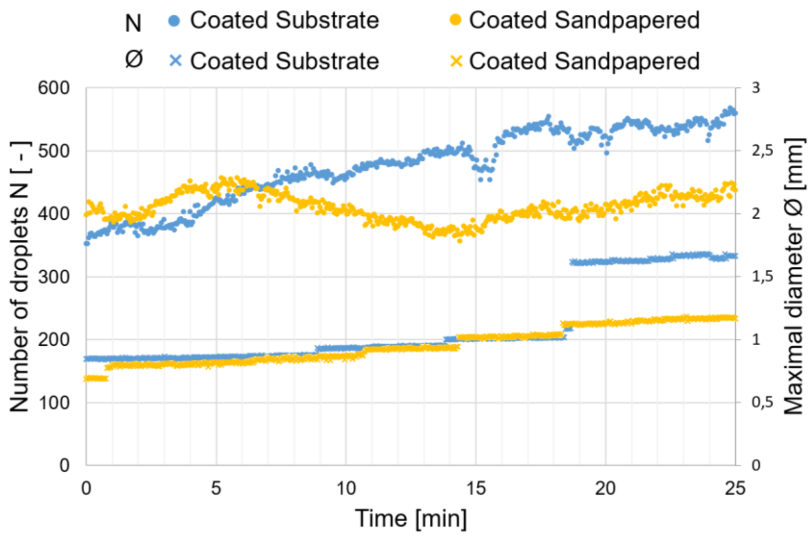
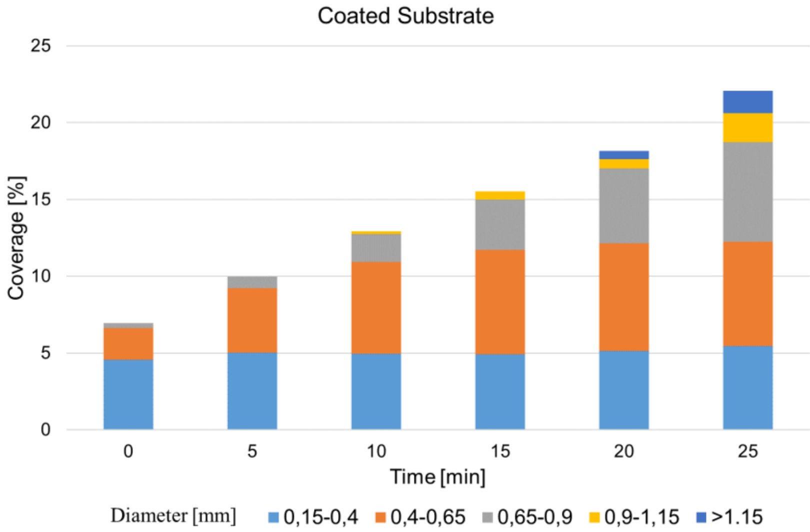
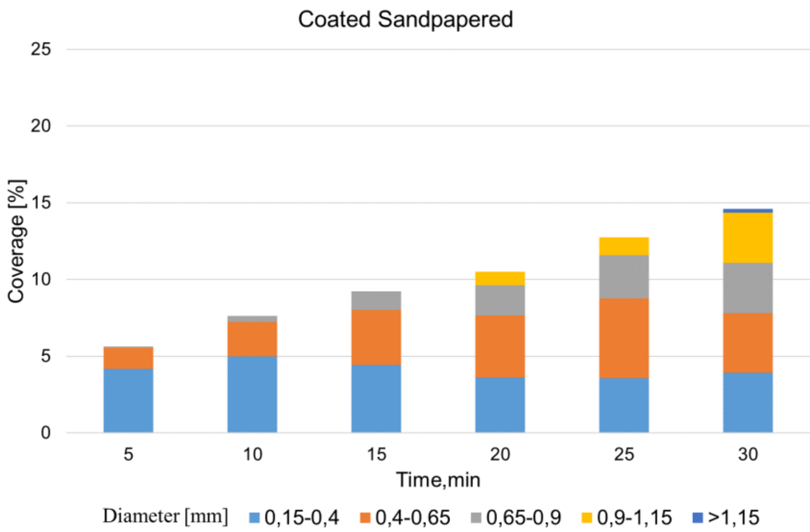


Fig. 3: Condensate droplet distribution parameters in time on both superhydrophobic samples: left Y-axis corresponds to the total number of droplets and right Y-axis to the maximal diameter of droplets

The coverage of experimental samples with condensate droplets of certain diameters is presented in Figure 4. Most of the droplets had the diameters less than 0.65 mm, indicating a rapid renewal of the cooling surface, which is common for the superhydrophobic surfaces. The larger droplets with diameters higher than 0.9 mm covered less than 5% of the surfaces on both samples. The surface coverage was expectedly rising in time, as more steam was condensed on the samples. At the end of the condensation experiments the coverage was less than 25 % on both samples. The value correlates well with the study of Chu et al. 2017, who also measured the surface coverage fraction to be within 20 – 30 % on the horizontal superhydrophobic surface under the similar condensation conditions. It is a quite low percentage, comparing to the surface coverage of around 40 – 60 % reported for the hydrophobic surfaces during the dropwise condensation (Chu 2017). The reason for that is that the surface coverage decreases, as the apparent contact angle of the surface increases, which is the case with superhydrophobic surfaces.



a)



b)

Fig. 4: Surface coverage with condensate droplets during condensation on the superhydrophobic samples: a) Coated Substrate and b) Coated Sandpapered

The experimental images of the coated substrate sample at the beginning of condensation process (0 minute) and at the end (25 minute) were verified by the ImageJ software. As presented in Table 2, the considered parameters showed a good agreement with the developed Matlab® code. For example, the difference in the surface coverage was less than 5 % at any time.

Tab. 2: Verification of the considered parameters determined by the developed Matlab algorithm and by the open source program ImageJ

Sample:	0 min		25 min	
Coated Substrate	Matlab	ImageJ	Matlab	ImageJ
Number of Droplets	352	344	559	539
Max diameter [mm]	0.84	0.73	1.66	1.59
Coverage [%]	6.9	6.6	22.1	21.7

Conclusions

Summarizing, the current work showed that the considered distribution characteristics of condensate droplets were similar on both superhydrophobic-coated samples, independent of the previous mechanical sample treatment. The surface coverage with condensate droplets was, as expected, rising in time and was less than 25 % for both samples at the end of the condensation experiment. Most of the droplets had the diameters less than 0.65 mm, indicating a rapid renewal of the cooling surface via the out-of-plane jumping, which can happen on superhydrophobic surfaces. Moreover, the developed Matlab® pattern recognition tool proved to be quite reliable and beneficial for the automatic analysis of large amount of experimental images taken during the dropwise condensation on the superhydrophobic surfaces.

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Author contributions

Project Administration, N.F. and V.J.; Conceptualization, N.F., V.J., A.Z.-R. and A.D.; Supervision, N.F., M.M and V.J.; Methodology, N.F., R.B., M.M. and V.J.; Investigation, N.F., R.B. and M.M.; Data Curation, R.B., N.F., M.M, V.J. and A.Z.-R.; Visualization, N.F., R.B. and M.M; Validation, R.B., N.F. and M.M.; Writing—Original Draft Preparation, N.F., R.B., M.M., V.J. and A.Z.-R.; Funding acquisition, V.J. and A.D., Resources, V.J. and A.D. The present work was performed in (partial) fulfilment of the requirements for obtaining the doctoral degree “Dr. Ing.” of the Friedrich-Alexander University Erlangen-Nuremberg, Technical Faculty for Nataliia Fedorova, who qualifies as the lead author.

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