

Global sensitivity analysis of a pure steam dropwise condensation heat transfer model

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Abstract

In recent years, established heat transfer models for dropwise condensation (DWC) have been refined to consider the influence of wetting behavior, surface structure and nucleation dynamics on the heat transfer rate in more detail. Despite these efforts to develop more sophisticated models, uncertainties of the model parameters still lead to a high variation of the calculated heat transfer rate. In this study, we apply quantitative sensitivity analysis to a pure steam DWC heat transfer model in order to attribute the variation of the model result to its input parameters. Four scenarios with different variations of the model parameters are discussed and sensitivity coefficients for each parameter are calculated. Our results show that the contact angle and the nucleation site density have the greatest influence on the model result if no additional coating layer is considered. The influence of the nucleation site density is mainly due to the large uncertainties associated with this parameter. In scenarios with an additional coating layer, the heat flux is mainly governed by the thickness of the coating layer, underlining the need for thin conformal coatings to effectively promote DWC. Furthermore, trends within the heat transfer model are discussed and beneficial conditions for a high heat flux are identified for each scenario. The results underline that the wetting properties of functional surfaces should be tailored towards medium contact angles in the range of 70° to 130° and low contact angle hystereses below 10° to achieve high heat flux DWC.

Keywords: dropwise condensation, heat transfer enhancement, sensitivity analysis, nucleation

Nomenclature

Bo	Bond number
$E(\cdot)$	expected value of argument ($\cdot$)
g	gravitational acceleration, $m\ s^{-2}$
j	base sample size
J	sample size
k	number of model input parameters
l_c	capillary length, m
n	small drops size distribution, m^{-3}
N	large drops size distribution, m^{-3}
N_s	nucleation site density, m^{-2}
p	pressure, kPa
$\dot{q}$	heat flux, $W\ m^{-1}$
$\dot{Q}_d$	heat flow rate through a single drop, W
r	drop radius, m
r_e	effective drop radius, m
r_{max}	maximum drop radius, m
r_{min}	minimum drop radius, m
R_g	specific gas constant, $J\ kg^{-1}\ K^{-1}$
S_T	total effects sensitivity index
T_{sat}	saturation temperature, K
$Var(\cdot)$	variance of argument ($\cdot$)
X_i	model input parameter
$\mathbf{X}_{\sim i}$	$J \times (k - 1)$ matrix of all parameters but X_i
Y	model result

Greek symbols

α^*	equivalent heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
α_{lg}	interfacial heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
δ_c	coating thickness, μm
Δh_v	latent heat of vaporization, $kJ\ kg^{-1}$
ΔT_c	temperature difference due to the conduction through the coating layer, K
ΔT_{curv}	temperature difference due to drop curvature, K
ΔT_d	temperature difference due to the conduction through the drop, K
ΔT_i	temperature difference due to interfacial resistance, K
ΔT_{sub}	subcooling temperature difference, K

$\Delta\theta$	contact angle hysteresis, deg
θ	contact angle, deg
θ_a	advancing contact angle, deg
θ_r	receding contact angle, deg
λ_c	thermal conductivity of the coating, W m ⁻¹ K ⁻¹
λ_l	thermal conductivity of the condensate, W m ⁻¹ K ⁻¹
ρ_g	vapor density, kg m ⁻³
ρ_l	liquid density, kg m ⁻³
σ_{lg}	surface tension, N m ⁻¹
τ	sweeping period, s
<i>Subscripts</i>	
c	coating
d	drop
g	vapor phase
l	liquid phase
lg	liquid vapor interphase
<i>Abbreviations</i>	
DWC	dropwise condensation
PTFE	Polytetrafluoroethylene

1. Introduction

The potential for an enhanced heat transfer compared to filmwise condensation has motivated extensive research on dropwise condensation (DWC) for over 90 years [1,2]. Beside the question of how to promote this superior condensation mode in heat exchangers, the modeling and calculation of the heat flux during DWC is a central topic of this research. In 1966, Le Fevre and Rose published a fundamental model for the heat transfer during DWC [3]. In this model, a characteristic density distribution of the drop sizes is calculated and then combined with the size-dependent heat flow rate through a single drop. This conceptual modeling approach continues to be the basis for a majority of the models for DWC [4]. Both aspects of the model – the heat flow rate through a single drop and the drop size distribution – have been intensively discussed and refined in numerous publications. Important developments in DWC modeling include the application of population balance methods to calculate the drop size distribution for small drops [5,6], the consideration of non-hemispherical drops with contact angles over 90° [7] and the modeling of the heat transfer on advanced functional surfaces like superhydrophobic nanostructured surfaces [8–11] and lubricant-infused surfaces [10,12,13]. Extensive reviews are available on the topic of DWC modeling [4,14–16].

Despite these considerable efforts, model results often deviate from experiments. Recently, Wang et al. have compared the model results of typical DWC heat transfer models with experimental data from the literature and found that existing models are not generally applicable to various conditions during DWC [17]. Similar comparisons of model results and experimental data have been used by other researchers to validate heat transfer models for DWC [6,7,18–20]. If significant deviations between model and experimental results occur, they are often explained with a lack of detail in the investigated heat transfer model or with experimental errors like inaccurate heat transfer measurements and the presence of non-condensable gases [2,14]. While

both of these explanations can be valid, deviations can also result from inaccurate values for the model input parameters.

Naturally, all DWC heat transfer models rely on measurements, estimations and assumptions regarding their input parameters. All values of the model input parameters are therefore associated with an uncertainty. Some input parameters of the DWC models are notoriously difficult to measure or calculate. This is especially true for the parameters associated with the nucleation process of new drops. Most of the DWC models calculate radius of newly formed drops using classical nucleation theory. It is then assumed that new drops form at specific nucleation sites on the surface as soon as they are not occupied by another drop. These new drops are very small and grow rapidly during condensation, which makes any direct observation of the process difficult. Thus, experimental results to support the assumptions regarding nucleation during DWC are scarce. At the same time, it is often not possible to reliably calculate all the relevant model parameters from theory. Classical nucleation theory is known to be unreliable in predicting experimental results in other cases such as homogeneous nucleation of argon [21–23]. Despite these known issues, the uncertainties associated with model input parameters like the nucleation site density are rarely considered when modeling DWC, even though they can be significant and may lead to a high variation in the calculated heat flux.

In order to systematically refine and validate existing models, it is essential to know how the variation of the model result can be attributed to each of the model input parameters. The parameters that have the greatest influence on the model result should be identified so that researchers can focus their modeling and experimental efforts on improving the data basis for DWC modeling where necessary. In this theoretical study, we apply variance based quantitative sensitivity analysis to a DWC heat transfer model in order to establish a ranking of the model input parameters based on their total sensitivity indices in four different scenarios. The scenarios are defined with regard to physical plausibility (scenarios 1 and 2) and information

from measurements (scenarios 3 and 4). In addition to the quantitative sensitivity analysis, we identify and discuss regions in the input parameter space for each scenario that lead to high heat fluxes according to the DWC heat transfer model.

2. Dropwise condensation model

2.1 Heat transfer model

Starting point for the modeling of the heat flow in this study is the model by Kim and Kim published in 2011 [7]. This model follows the modeling approach by Le Fevre and Rose [3] and is suitable as a point of reference since it represents a significant extension of previous models by including non-hemispherical drops. At the same time, the model is formulated in general terms, so that its application is not limited to specific surfaces. The heat flux $\dot{q}$ during DWC is calculated from equation (1)

$$\dot{q} = \int_{r_{\min}}^{r_e} \dot{Q}_d(r)n(r)dr + \int_{r_e}^{r_{\max}} \dot{Q}_d(r)N(r)dr \quad (1)$$

where $\dot{Q}_d(r)$ is the heat flow rate through a single drop of the radius r , $n(r)$ is the drop size distribution for small drops with a radius between the minimum drop radius $r_{\min}$ and the effective drop radius r_e and $N(r)$ is the drop size distribution for large drops with radii up to the maximum drop radius $r_{\max}$. As derived by Kim and Kim [7], the heat flow rate through a single drop is given by equation (2)

$$\dot{Q}_d = \frac{\Delta T_{\text{sub}} \pi r^2 \left(1 - \frac{r_{\min}}{r}\right)}{\frac{1}{2\alpha_{1g}(1-\cos\theta)} + \frac{r\theta}{4\lambda_1 \sin\theta} + \frac{\delta_c}{\lambda_c \sin^2\theta}} \quad (2)$$

where ΔT_{sub} is the subcooling temperature, θ is the contact angle, λ_1 is the thermal conductivity of the condensate, δ_c is the coating layer thickness and λ_c the thermal conductivity of the coating. The interfacial heat transfer coefficient α_{1g} is calculated from fluid properties (specific

gas constant R_g , saturation temperature T_{sat} , latent heat of vaporization Δh_v and vapor phase density ρ_g) using equation (3) [24].

$$\alpha_{\text{lg}} = \frac{2}{\sqrt{2\pi R_g T_{\text{sat}}}} \frac{\Delta h_v^2 \rho_g}{T_{\text{sat}}} \quad (3)$$

Since the primary mechanism of drop growth changes depending on the drop size, two regions are distinguished in the drop size distribution: very small drops that grow primarily by direct condensation on the drop surface and larger drops that grow primarily by coalescence with other drops [25,26]. For large drops, the drop size distribution is calculated according to the equation given by Le Fevre and Rose [3] as a function of the maximum drop radius that is occurring on the surface before the drop is removed by gravity or external forces.

$$N(r) = \frac{1}{3\pi r^2 r_{\text{max}}} \left(\frac{r}{r_{\text{max}}} \right)^{-2/3} \quad (4)$$

The drop size distribution for small drops is depending on nucleation processes during condensation. It is calculated based on the population balance method [6] using the following equations [7].

$$n(r) = \frac{1}{3\pi r_e^3 r_{\text{max}}} \left(\frac{r}{r_{\text{max}}} \right)^{-2/3} \frac{r(r_e - r_{\text{min}})}{r - r_{\text{min}}} \frac{A_2 r + A_3}{A_2 r_e + A_3} \exp(B_1 + B_2) \quad (5)$$

$$A_1 = \frac{\Delta T_{\text{sub}}}{2\rho_l \Delta h_v} \quad (6)$$

$$A_2 = \frac{\theta(1 - \cos \theta)}{4\lambda_l \sin \theta} \quad (7)$$

$$A_3 = \frac{1}{2\alpha_{\text{lg}}} + \frac{\delta_c(1 - \cos \theta)}{\lambda_c \sin^2 \theta} \quad (8)$$

$$B_1 = \frac{A_2}{\tau A_1} \left[\frac{r_e^2 - r^2}{2} + r_{\min}(r_e - r) - r_{\min}^2 \ln \left(\frac{r - r_{\min}}{r_e - r_{\min}} \right) \right] \quad (9)$$

$$B_2 = \frac{A_3}{\tau A_1} \left[r_e - r - r_{\min} \ln \left(\frac{r - r_{\min}}{r_e - r_{\min}} \right) \right] \quad (10)$$

$$\tau = \frac{3r_e^2(A_2r_e + A_3)^2}{A_1(11A_2r_e^2 - 14A_2r_er_{\min} + 8A_3r_e - 11A_3r_{\min})} \quad (11)$$

The drop size distribution for small drops is therefore depending on the fluid properties, the minimum drop radius $r_{\min}$, the effective drop radius r_e , the contact angle θ , as well as the coating thickness δ_c and heat conductivity of the coating layer λ_c . The minimum drop radius is in turn calculated from fluid properties and surface subcooling based on classical nucleation theory using equation (12)

$$r_{\min} = \frac{2T_{\text{sat}}\sigma_{\text{lg}}}{\Delta h_v \rho_l \Delta T_{\text{sub}}} \quad (12)$$

where σ_{lg} is the surface tension and ρ_l is the density of the condensate. In the model by Kim and Kim [7], the subcooling temperature ΔT_{sub} includes the temperature drop due to interfacial resistance ΔT_i , the temperature drop due to drop curvature ΔT_{curv} , the temperature drop due to conduction through the drop ΔT_d as well as the temperature drop due to the conduction through the coating layer ΔT_c .

$$\Delta T_{\text{sub}} = \Delta T_i + \Delta T_{\text{curv}} + \Delta T_d + \Delta T_c \quad (13)$$

We adopt this definition since it simplifies the calculation of the heat flux with equation (1). With regard to equation (12) it should be noted that, by including the temperature drop due to the conduction through the coating layer, this definition of the subcooling temperature leads to

an underestimation of the minimum drop radius. The interrelation between the minimum drop radius and the thermal resistance of the coating is discussed in detail elsewhere [27].

For the effective drop radius, the following relationship with the nucleation site density N_s follows from a simplified geometric consideration that assumes an arrangement of the nucleation sites in form of a square array [7].

$$r_e = (4N_s)^{-1/2} \quad (14)$$

The maximum drop radius on a vertical wall is calculated based on the force balance between surface tension and gravity using the following equation [7].

$$r_{\max} = \left(\frac{6\sigma_l g (\cos \theta_r - \cos \theta_a) \sin \theta}{\pi \rho_l g (2 - 3 \cos \theta + \cos^3 \theta)} \right)^{1/2} \quad (15)$$

To reduce the number of model input parameters for the sensitivity analysis, the advancing contact angle θ_a and the receding contact angle θ_r are calculated from the contact angle hysteresis $\Delta\theta$ based on the assumption that the contact angle is the arithmetic mean of the two values:

$$\theta_a = \theta + \frac{\Delta\theta}{2} \quad (16)$$

$$\theta_r = \theta - \frac{\Delta\theta}{2} \quad (17)$$

Using equations (2) – (17), the heat flux is calculated from equation (1) for a given subcooling temperature. The aim of this study is to evaluate the influence of the model parameters on the heat transfer efficiency calculated by the model. Therefore, the subcooling temperature is not considered as a model parameter. Instead, an equivalent heat transfer coefficient α^* is defined in equation (18) and calculated from two subcooling temperatures and their corresponding heat fluxes.

$$\alpha^* = \frac{1}{2} \left(\frac{\dot{q}_1}{\Delta T_{\text{sub},1}} + \frac{\dot{q}_2}{\Delta T_{\text{sub},2}} \right) \quad (18)$$

Subcooling temperatures of $\Delta T_{\text{sub},1} = 1$ K and $\Delta T_{\text{sub},2} = 10$ K are used for the sensitivity analysis. According to the definition of the subcooling temperature in equation (13), the equivalent heat transfer coefficient includes the heat transfer from the fluid to the surface of the coating layer as well as the thermal conduction through the coating layer.

2.2 Dropwise condensation criterion

The heat transfer model allows for a calculation of the mean heat transfer coefficient for arbitrary combinations of input parameters. However, the model provides no information as to whether DWC actually occurs with the given input parameters. Recently, Cha et al. have proposed a criterion for dropwise to filmwise transition based on the Bond number Bo of the largest drop immediately before departure [28]. We adopt this criterion and assume that DWC occurs only if $Bo \leq 1.4$. The Bond number for a drop in equilibrium immediately before departure is defined as follows.

$$Bo = \frac{r_{\text{max}}^2}{l_c^2} \quad (19)$$

The capillary length l_c is defined as

$$l_c = \sqrt{\frac{\sigma_{lg}}{\rho_l g}} \quad (20)$$

where g is the gravitational acceleration. Using equations (15), (19) and (20) the Bond number can be calculated based on the contact angles alone.

$$Bo = \frac{6(\cos \theta_r - \cos \theta_a) \sin \theta}{\pi(2 - 3 \cos \theta + \cos^3 \theta)} \quad (21)$$

Dropwise to filmwise transition due to nucleation site saturation [29] is not considered in this work since it depends heavily on the surface subcooling temperature, which is not investigated in the sensitivity analysis.

2.3 Input parameters

With regard to the equations above, the following six input parameters are required to calculate the heat flux for a given subcooling temperature with equation (1):

- contact angle θ
- contact angle hysteresis $\Delta\theta$
- the fluid properties of the saturated steam and condensate, which can be calculated from the pressure p for a specific fluid
- the nucleation site density N_s
- the thickness of the coating δ_c
- the thermal conductivity of the coating λ_c

In order to calculate the large number of model results required for the sensitivity analysis, the model is implemented in the python programming language. For the sensitivity analysis, pure water is considered as the condensing fluid. All fluid properties are calculated using the CoolProp library [30].

3. Variance based global sensitivity analysis

3.1 Sampling method and sensitivity index

The aim of the sensitivity analysis is to attribute the variation of the equivalent heat transfer coefficient calculated with the DWC heat transfer model to the input parameters of the model [31]. Variance based sensitivity analysis allows this attribution to be quantified in form of a

sensitivity index with a numeric value between 0 and 1 for each input parameter. In this study, the *total effect sensitivity indices* $S_{T,i}$, as introduced by Homma and Saltelli [32], are calculated for each input parameter according to the method of Sobol' [33]. The total effect sensitivity index provides a measure for the overall effect of each input parameter on the model results, including direct effects as well as interactions with all other input parameters [32]. In this study, the aim of the sensitivity analysis is to establish a *ranking* (or *factor prioritization*) [31,33] of the input parameters of the DWC heat transfer model with regard to their relative importance in determining the model result. The uncertainties of input parameters with high total effect sensitivity indices affect the model result the most, while input parameters with a low total effect sensitivity index have only little influence on the variation of the model result. In order to calculate the total effect sensitivity indices, an input parameter space is defined by choosing a value range for each input parameter. The value ranges are chosen based on their physical meaning, information from the literature or previous measurements. A number of samples are then generated from the input parameter space by using the sampling strategy established by Saltelli et al. [34,35]. A base sample size of $j = 1000$ is chosen, resulting in J samples for each scenario, depending on the number of input parameters k [34]:

$$J = j(2k + 2) \quad (22)$$

For these samples, the equivalent heat transfer coefficients are calculated with the DWC heat transfer model. The total effect sensitivity index $S_{T,i}$ for a given model input parameter X_i with $i = 1, \dots, k$ is defined in equation (22) [35]

$$S_{T,i} = 1 - \frac{\text{Var} [\mathbb{E}(Y | \mathbf{X}_{\sim i})]}{\text{Var} [Y]} \quad (23)$$

where Y is the model result (in this case the equivalent heat transfer coefficient) and $\mathbf{X}_{\sim i}$ is a $J \times (k - 1)$ matrix of all model input parameters except for X_i . The total effect sensitivity

indices are then calculated from the input parameter samples and their corresponding model results according to the method of Sobol' [33]. For the sampling of the input parameter space as well as for the calculation of the sensitivity indices, the python library SALib [36] is used. The python code used to produce the results and figures in this paper is available online [37].

3.2 Definition of input parameter space

The sensitivity of the model with respect to the various input parameters is largely determined by the value ranges of the input parameters. Depending on the definition of the value ranges, different statements can be made about the model based on the sensitivity analysis. Two main aspects are considered separately in the definition of the input parameter space: 1) the influence of the coating and 2) the influence of the range of the input parameters. This results in four scenarios for the sensitivity analysis. In scenario 1 and 2, a wide range of input parameters is considered without any coating and with an additional coating layer, respectively. Scenario 3 and 4 are defined with a more narrow range of the input parameters, again without (scenario 3) and with (scenario 4) an additional coating layer. In the following, the four scenarios are defined and their motivation is explained in detail. Table 1 provides an overview over the input parameter space for all scenarios.

Table 1 Input parameter space for all four scenarios.

	θ / deg	p / kPa	N_s / m ⁻²	$\Delta\theta$ / deg	δ_c / μm	λ_c / (W m ⁻¹ K ⁻¹)
Scenario 1	5 ... 175	5 ... 500	$10^9 \dots 10^{15}$	1 ... 90	no coating	no coating
Scenario 2	5 ... 175	5 ... 500	$10^9 \dots 10^{15}$	1 ... 90	0.1 ... 50	0.2 ... 10
Scenario 3	83 93	11 ... 13	$10^9 \dots 10^{15}$	24 ... 44	no coating	no coating
Scenario 4	83 93	11 ... 13	$10^9 \dots 10^{15}$	24 ... 44	0.1 ... 1	5 ... 10

In scenario 1, DWC on an uncoated surface is assumed. The input parameters (contact angle, contact angle hysteresis, nucleation site density and pressure) are varied over a wide range. Therefore, a wide spread of the model results can be expected. The purpose of this scenario is to investigate the maximum range for the calculated equivalent heat transfer coefficients and to investigate basic correlations between the input parameters and the model results. The value ranges are chosen based on the criterion of physical and technical plausibility. For the contact angle the whole range from very hydrophilic ($\theta = 5^\circ$) to very hydrophobic ($\theta = 175^\circ$) is considered. The contact angle hysteresis is varied from 1° to 90° . Due to the wide range of values for both the contact angle and the contact angle hysteresis, equations (16) and (17) give advancing contact angles of $\theta_a > 180^\circ$ or receding contact angles of $\theta_r < 0^\circ$ in some cases. In those cases, $\theta_a = 180^\circ$ or $\theta_r = 0^\circ$ is assumed, respectively. These combinations of contact angle and contact angle hysteresis are still used for the calculation of the sensitivity indices but not shown in the scatterplots in section 4.2. For the vapor pressure, a value range of 5 kPa to 500 kPa is selected against the background of possible technical applications. The value range of the nucleation site density is defined as $10^9 \text{ m}^{-2} < N_s < 10^{15} \text{ m}^{-2}$ based on values from the literature given in Table 2.

Table 2 Orders of magnitude for the nucleation site density N_s from the literature.

N_s / m^{-2}	Type of surface or promoter and reference
10^9	Fluorinated thiol coating [9]
10^{10}	Fluorinated silane coating [9], hydrophobic polymer film and a silanized glass [38]
$10^{10} \dots 10^{11}$	Various metal surfaces [39]
10^{11}	Superhydrophobic surface [7], lubricant infused surface [12], PTFE and dioctadecyl disulphide [6]
$10^{11} \dots 10^{12}$	Sol-gel coating on aluminum substrate [40]
10^{12}	Copper with dioctadecyl disulphide promoter [41]
10^{14}	Various functionalized titanium surfaces [18]
$10^{13} \dots 10^{15}$	Theoretical study [42]

Scenario 2 corresponds to scenario 1 and additionally, the influence of a coating layer is taken into account. The parameters of the coating layer are varied in a wide range of values of $0.1 \mu\text{m}$ to $50 \mu\text{m}$ for the coating thickness and $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ to $10 \text{ W m}^{-1} \text{ K}^{-1}$ for the thermal conductivity of the coating. The ranges are defined based on technical considerations: coatings with a thickness below $0.1 \mu\text{m}$ tend to be not robust enough for technical applications. With regard to the thermal resistance, the coating thickness was limited to $50 \mu\text{m}$. The value range for the thermal conductivity coefficients was determined based on potential coating materials (e.g. approximately $0.2 \text{ W m}^{-1} \text{ K}^{-1}$ for PTFE and $10 \text{ W m}^{-1} \text{ K}^{-1}$ for composite coatings [43]).

In Scenario 3, DWC on an uncoated surface is considered. In contrast to scenario 1, the input parameter space is more narrowly defined. Previous condensation experiments on a mirror-finished stainless steel sample serve as orientation. The value ranges were chosen to reflect the uncertainty associated with the measurement of each input parameter. To our knowledge, there is currently no experimental procedure available to measure the nucleation site density directly. Instead of a direct measurement, the values for this model parameter have to be estimated based on data from the literature. Therefore, the same range of values as in scenario 1 and 2 is used.

The aim of the sensitivity analysis with this scenario is to consider the effects of the measurement uncertainties of all input parameters on the model result. This is intended to make a statement as to which input parameters should be determined more precisely in experiments in order to better validate the model.

Scenario 4 corresponds to scenario 3, but the additional influence of a coating layer is considered. The range of values is selected in such a way that the coatings have beneficial properties for the heat transfer (small coating thickness in the range of range of 0.1 μm to 1 μm and high thermal conductivity in the range of 5 $\text{W m}^{-1} \text{K}^{-1}$ to 10 $\text{W m}^{-1} \text{K}^{-1}$).

4. Results and discussion

4.1 Quantitative sensitivity analysis

Deviations between the heat transfer model and DWC experiments can result from the model structure as well as from uncertainties associated with the model input parameters (which might be measured or calculated). In many studies, the uncertainty of the model input parameters is not considered as part of the model validation. To assess, which model input parameters have the greatest influence on the variation of the model result, the total effect sensitivity indices are calculated for the four DWC scenarios.

The total effect sensitivity indices are shown in Fig. 1. Overall, it is clear that in the scenarios with a coating layer (scenario 2 and scenario 4), the thermal resistance of the coating (thermal conductivity and coating thickness) has a crucial influence on the calculated heat transfer coefficient. This also applies to the case of a coating with a low coating thickness and comparatively high thermal conductivity (scenario 4). In addition to the thermal conductivity of the coating, the model result depends above all on the contact angle (scenarios 1 and 2) and the nucleation site density (scenarios 3 and 4).

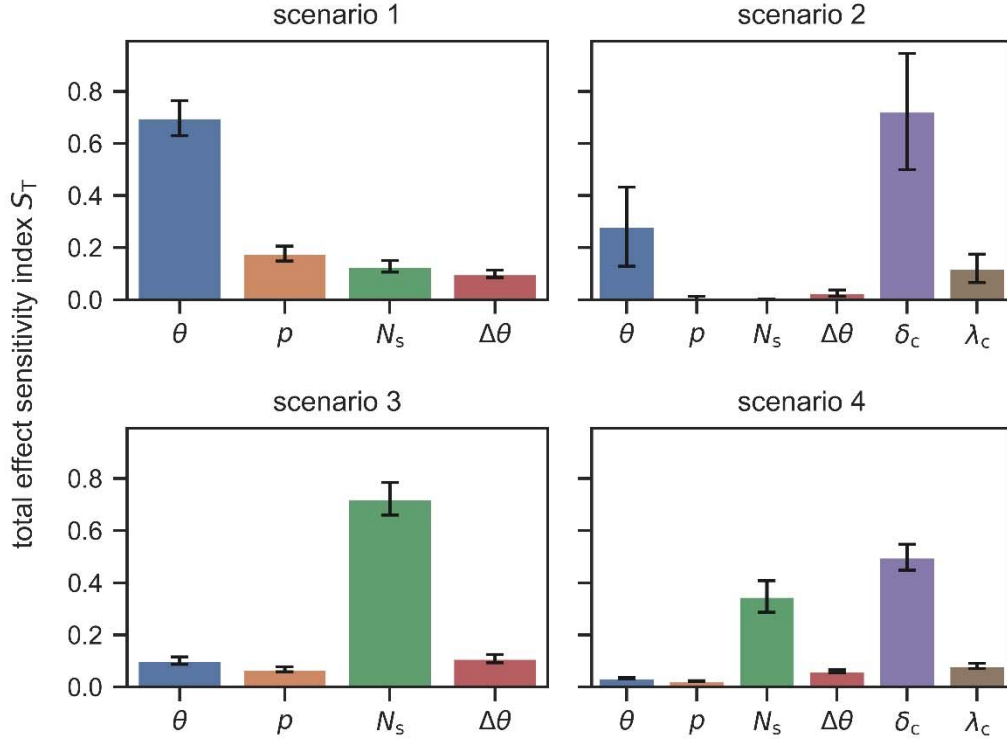


Fig. 1. Total effect sensitivity indices S_T for the four scenarios. Scenarios 1 and 2 represent a wide input parameter space without and with a coating layer, respectively. Scenarios 3 and 4 represent a more narrow input parameter space without and with a coating layer, respectively. Model input parameters are: contact angle θ , pressure p , nucleation site density N_s , contact angle hysteresis $\Delta\theta$, coating thickness δ_c and thermal conductivity of the coating λ_c . Error bars indicate the 0.95 confidence level.

The influence of the nucleation site density on the model result is particularly strong in scenario 3. In this scenario, the input parameter space is narrowed down to reflect the information that can be gained by DWC experiments and contact angle measurements. In the case of the nucleation site density, there are no additional information obtainable from direct measurements, which leads to the high sensitivity index of the nucleation site density observed in scenario 3. This means that, due to the high uncertainty associated with the nucleation site density, the heat flux calculated by the model can deviate from experimental results even if the heat transfer model itself is perfectly accurate and the experiments are conducted with great care.

The high sensitivity index of the nucleation site density in scenario 3 also offers a starting point for the experimental determination of the nucleation site density. Using model calibration [31] the nucleation site density could be estimated from experimental data if the other model parameters, the heat flux and the subcooling temperature are measured accurately. Ideally, these experiments are performed on uncoated or very precisely coated samples in order to minimize the influence of the coating layer as investigated in scenario 4. A prerequisite for this experimental determination of the nucleation site density is that the heat transfer model represents the actual processes during DWC with sufficient accuracy. In particular, additional effects on the heat transfer, that are not represented in the model (e.g. non-condensable gases), must not influence the experiments. Under these conditions, model calibration can be a useful approach for the investigation of nucleation phenomena in DWC allowing validation or adaptation of the previous models.

The total effect sensitivity indices provide a quantitative measure for the influence of each input parameter on the model result. However, they do not indicate any trends between the values of the input parameters and the model result. In order to identify regions in the input parameter space that lead to a high equivalent heat transfer coefficient, a qualitative sensitivity analysis of the DWC model is conducted in the following section.

4.2 Qualitative sensitivity analysis

4.2.1 Scenario 1

In this scenario, the input values for the model are varied over a very wide range, not taking into account the insulating effect of a coating. Under these conditions, the calculated heat transfer coefficient is most dependent on the contact angle of the condensate drops, while the

pressure, nucleation site density and contact angle hysteresis show low total effect sensitivity indices of less than 0.2.

Fig. 2 shows the influence of contact angle and pressure on the calculated heat transfer coefficient. Both influencing parameters show a clear tendency: The contact angle significantly reduces the heat transfer when it takes on very large or very small values. Very high heat transfer coefficients of over $1300 \text{ kW m}^{-2} \text{ K}^{-1}$ occur at medium contact angles between 70° and 130° . Over the entire range of contact angles, a higher pressure has a positive effect on the calculated heat transfer coefficients.

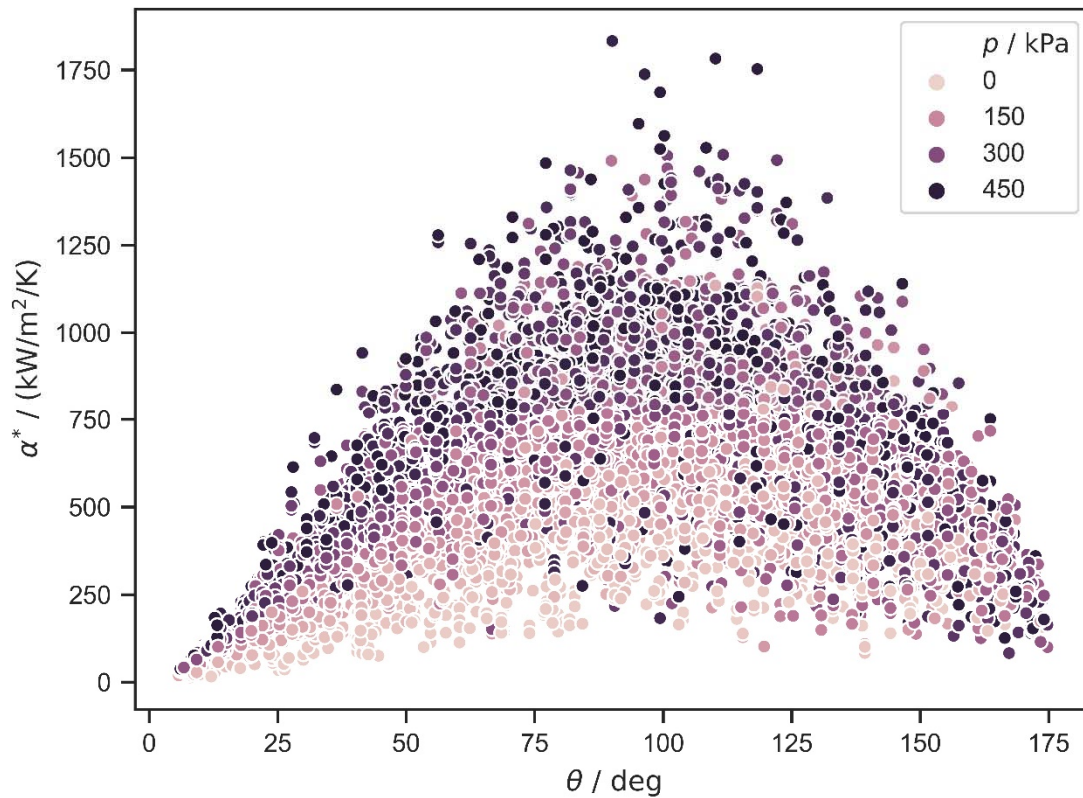


Fig. 2. Scenario 1 - equivalent heat transfer coefficient α^* vs. contact angle θ and pressure p .

Not all of the data points shown in Fig. 2 fulfill the DWC criterion of $Bo \leq 1.4$. Many data points in the hydrophilic region have high Bond numbers and filmwise condensation is expected for these combinations of input parameters. Fig. 3 shows only the data points for which DWC

is expected. It can be seen that DWC on hydrophilic surfaces with contact angles below 90° is only possible if the contact angle hysteresis is low enough. A very low contact angle hysteresis below 10° is necessary to achieve very high heat transfer coefficients of over $1300 \text{ kW m}^{-2} \text{ K}^{-1}$.

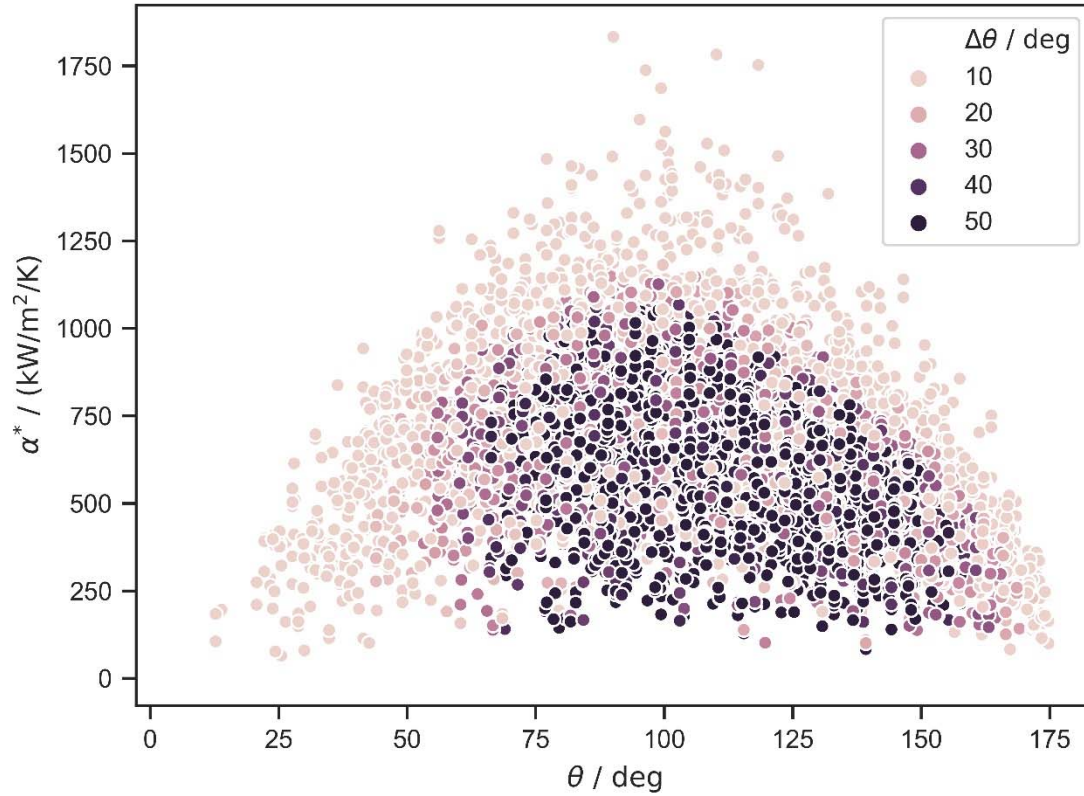


Fig. 3. Scenario 1 - equivalent heat transfer coefficient α^* vs. contact angle θ and contact angle hysteresis $\Delta\theta$, only data points with $Bo \leq 1.4$ are shown.

4.2.2 Scenario 2

This scenario corresponds to scenario 1, but additionally the insulating effect of a coating layer is considered. The thermal conductivity and the coating thickness are varied over a wide range. In this scenario, the layer thickness has the strongest influence on the calculated heat transfer coefficients. This is followed by the contact angle and the thermal conductivity of the coating.

Contact angle hysteresis, nucleation site density and pressure have a very small influence compared to these parameters.

Fig. 4 shows the influence of contact angle and coating thickness on the equivalent heat transfer coefficient. As in the previous scenario 1, it can be seen that the highest equivalent heat transfer coefficients are achieved at medium contact angles (indicated by dark points in the diagram). High equivalent heat transfer coefficients of more than $500 \text{ kW m}^{-2} \text{ K}^{-1}$ are only achieved in this scenario with very low coating thicknesses of less than $0.3 \mu\text{m}$.

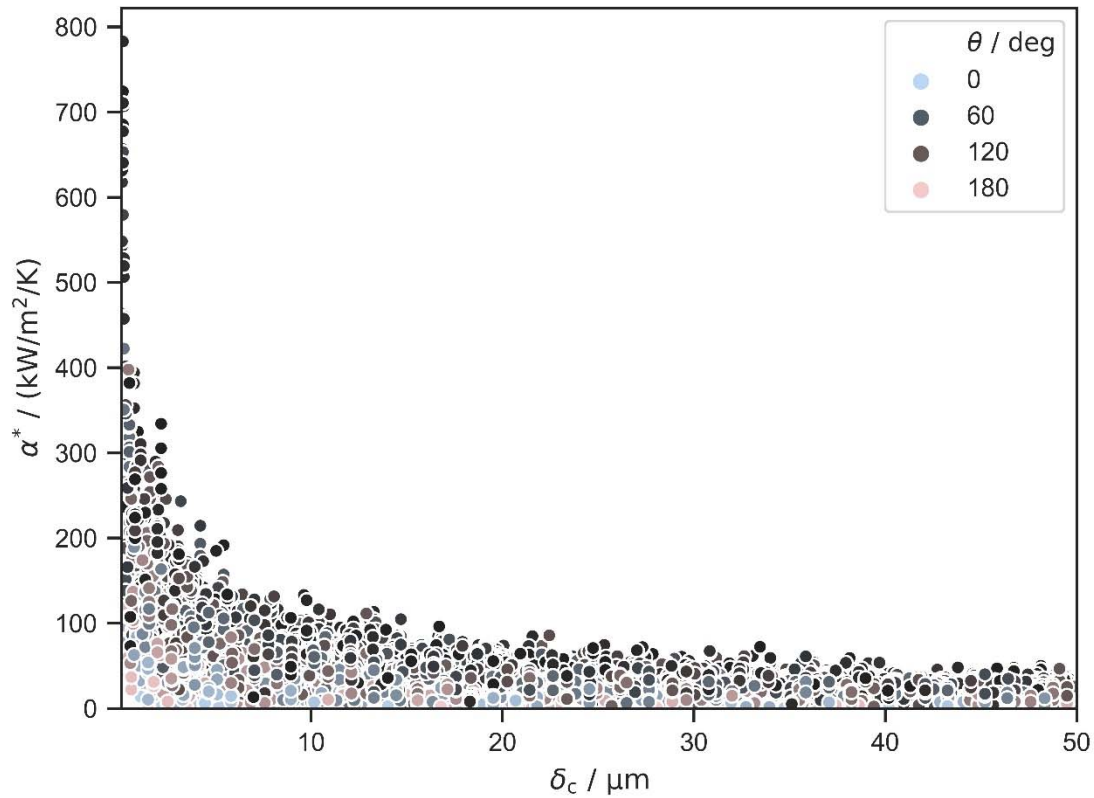


Fig. 4. Scenario 2 - equivalent heat transfer coefficient α^* vs. coating thickness δ_c and contact angle θ .

4.2.3 Scenario 3

In this scenario, no coating is considered. The other input parameters are varied in a narrow range to reflect the information obtainable by measurements. The nucleation site density cannot

be measured directly and is therefore associated with large uncertainties. This is also evident in the sensitivity coefficients of the model parameters: the nucleation site density has the greatest influence on the calculated heat transfer coefficients, by a clear margin to all other parameters. Fig. 5 shows the influence of the nucleation site density and the contact angle hysteresis on the heat transfer. A clear trend can be seen for both variables: with increasing nucleation site density and decreasing contact angle hysteresis, the heat transfer coefficient increases. The Bond numbers in this scenario range between 0.3 and 0.9, therefore the DWC criterion is satisfied for all datapoints.

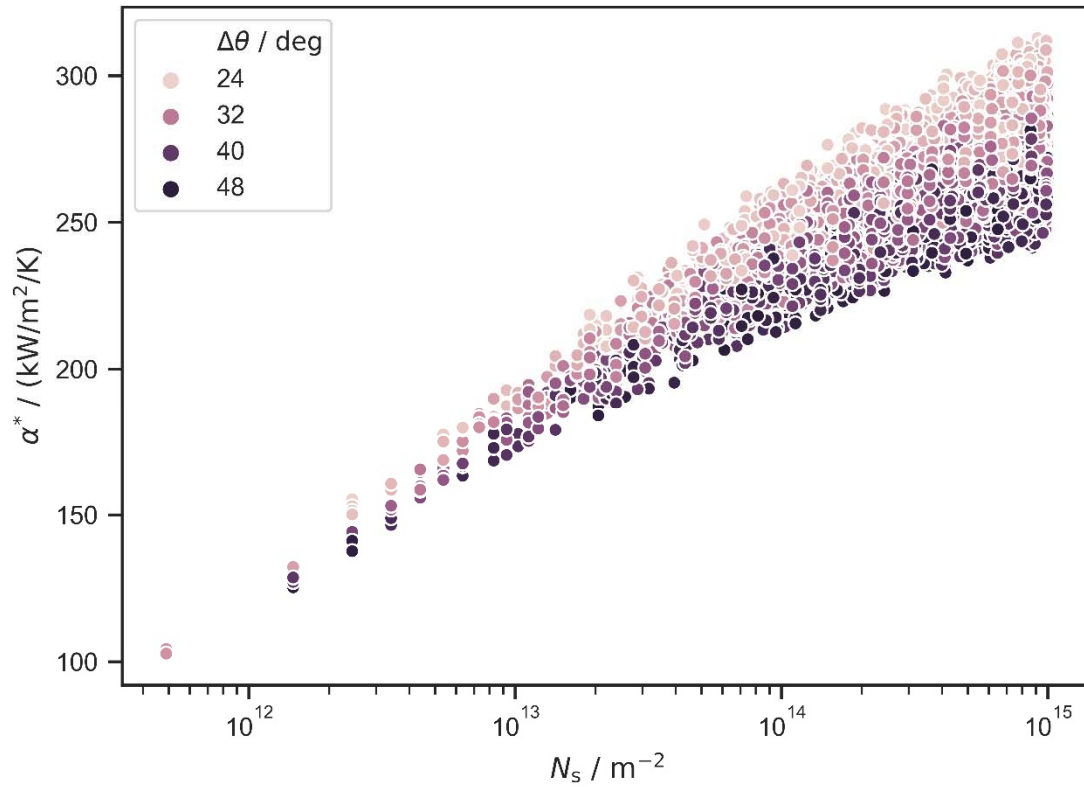


Fig. 5. Scenario 3 - equivalent heat transfer coefficient α^* vs. nucleation site density N_s and contact angle hysteresis $\Delta\theta$.

4.2.4 Scenario 4

This scenario corresponds to scenario 3, and additionally the influence of a coating layer is considered. Based on the results from scenario 2, a thin coating with thicknesses of less than 1 μm and with high thermal conductivity of $5 \text{ W m}^{-1} \text{ K}^{-1}$ to $10 \text{ W m}^{-1} \text{ K}^{-1}$ is chosen, so that high heat transfer coefficients are possible in principle. However, the model result in this scenario is still largely determined by the coating thickness, followed by the nucleation site density.

Fig. 6 shows the influence of layer thickness and nucleation site density. The trends for these two parameters described in scenarios 2 and 3 are confirmed in this scenario: the highest equivalent heat transfer coefficients occur with higher nucleation site densities and smaller coating thicknesses. Overall, the calculated heat transfer coefficients are in a similar range as in scenario 3. Due to the additional insulating effect of the coating, the values scatter more strongly in the direction of lower equivalent heat transfer coefficients, which is particularly evident at high nucleation site densities. Similar to scenario 3, the Bond number criterion of $Bo \leq 1.4$ is satisfied for all datapoints.

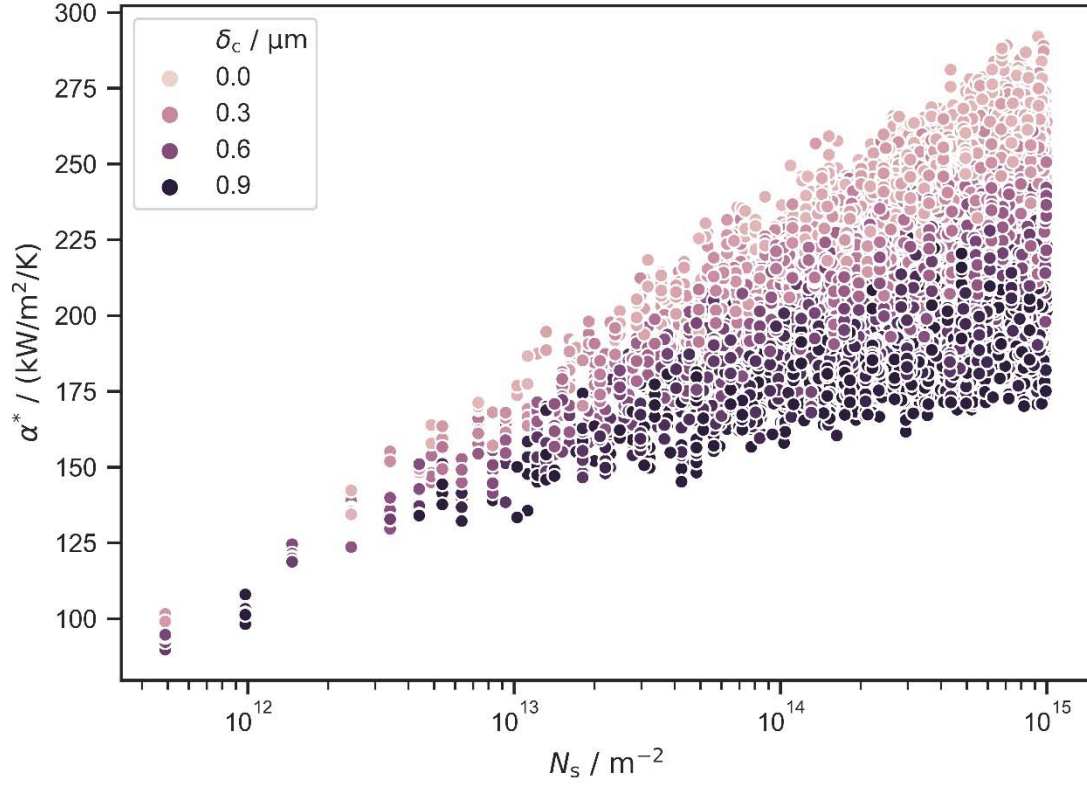


Fig. 6. Scenario 4 - equivalent heat transfer coefficient α^* vs. nucleation site density N_s and coating thickness δ_c .

5. Conclusions

In this study we presented quantitative and qualitative sensitivity analysis of a DWC heat transfer model. Our findings allow to attribute the variation of the model result to each of the model input parameters in four different scenarios. These results can serve as a guideline for future model development and validation as well as for the design of DWC experiments.

Using variance-based quantitative sensitivity analysis we found that the uncertainties in regard of the nucleation site density can have a significant influence on the calculated model result.

When the model parameters are varied over a very wide range (scenarios 1 and 2), the contact angle has a great influence on the calculated heat transfer coefficient. Qualitative sensitivity analysis showed that medium contact angles between 70° and 130° are optimal to achieve high

heat transfer coefficients according to the model. The contact angle hysteresis has less influence on the heat transfer coefficient but low values of less than 10° are preferable. In any case, the contact angle hysteresis must be low enough to facilitate DWC according to the Bond number criterion proposed by Cha et al. [28], especially on hydrophilic surfaces.

In scenario 3, which is considering a narrow input parameter space without any coating, it becomes clear that the variation of the model result can be attributed mainly to the nucleation site density. The reason for this is the high uncertainty associated with this parameter, which reflects the difficulties in reliably measuring or calculating the nucleation site density. The quantitative sensitivity analysis illustrates the high relevance that this aspect has for future DWC research. Considering the high sensitivity index of the nucleation site density, model calibration can be a viable approach to determine the value of this parameter experimentally and to allow for a closer investigation of nucleation phenomena in DWC.

Our results further underline the importance of minimizing the thermal resistance of any coating layer that is used to promote DWC. In the scenarios with a coating layer (scenarios 2 and 4), the coating thickness is the input parameter with the highest sensitivity index. This is the case, even if thin coatings with a coating thickness of less than $1\ \mu\text{m}$ and a high thermal conductivity in the range of $5\ \text{W m}^{-1}\ \text{K}^{-1}$ to $10\ \text{W m}^{-1}\ \text{K}^{-1}$ are considered, as shown in scenario 4.

In conclusion, the sensitivity analysis showed that the thermal resistance of the coating, the contact angle and the nucleation site density are the main parameters influencing the heat transfer during DWC. In order to maximize the heat flux during DWC, coatings should be as thin as possible, preferably less than $0.3\ \mu\text{m}$, and their wetting properties should be tailored towards average contact angles between 70° and 130° with a low contact angle hysteresis of less than 10° . Further research is needed to provide experimental data on the nucleation site density during DWC.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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