



Experimental analysis of steam condensation over conventional and superhydrophilic vertical surfaces



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ABSTRACT

Nano-engineered surfaces have been recently studied as a promising solution for many heat transfer applications. In particular, it is known that superhydrophobic surfaces, obtained by combining low surface free energy with micro-/nano-scale surface roughness, can promote dropwise condensation mode, while superhydrophilic ones, obtained for example by roughening the substrate to a micro-/nano-scale morphology, showed promotion of film formation during condensation. In the open literature there is a lot of information regarding the fabrication and characterization of these surfaces, but very few results on the heat transfer performance are reported.

In this paper, a new experimental apparatus for investigation of condensation of pure steam, flowing at different velocities, is presented. Filmwise condensation is investigated over untreated aluminum surfaces placed inside a rectangular narrow channel. The effect of wall subcooling and vapor velocity on the two-phase heat transfer coefficient is experimentally and theoretically analyzed. Condensation tests are also performed over a superhydrophilic surface, aiming at analyzing the effects of the wetting properties of the substrate on the process. A comparison between the heat transfer coefficients measured on the superhydrophilic surface and the ones obtained on the untreated sample shows a penalizing effect of the hydrophilic treatment.

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1. Introduction

Owing to their high water repellency, superhydrophobic surfaces have recently been studied as a promising solution to several challenges, such as drag reduction, anti-icing and enhancement of two-phase heat transfer performance [1–3]. Surface wettability is defined by the contact angles of a water drop sitting over it. For a static drop, an equilibrium contact angle is measured while, for moving drops, both the advancing and receding contact angles are taken as important parameters. The difference among the last two gives the contact angle hysteresis. Superhydrophobic surfaces present high contact angles, greater than 150°, and low contact angle hysteresis, lower than 10°. Superhydrophobic surfaces can be produced by combining two factors: micro-/nano-scale surface roughness and low surface free energy. Proper surface roughness can be obtained through different techniques, as micromachining, micro-contact-printing, chemical etching in aqueous solutions and deep radiative ion etching. Low surface energy can be obtained by coating the substrate with a thin layer of a material with small surface energy, such as organic substances, polymers, and noble

metals. These two elements allow water drops to sit over the surface with a quasi-spherical shape and to easily roll-off from it, being this a key factor for two-phase heat transfer applications. By producing a surface like the previous one but without lowering the surface free energy, one can obtain a superhydrophilic surface, i.e. with contact angle lower than 30°. While superhydrophobic surfaces are known to promote dropwise condensation, filmwise condensation mode is expected when using superhydrophilic surfaces [4].

Although hydrophilic surfaces are used to promote film condensation, data related to superhydrophilic surfaces are very rare in the literature. To fill this gap, the present paper focuses on steam condensation over a hydrophilic and a superhydrophilic aluminum surface to investigate the effect of high wettability.

When designing and fabricating an experimental apparatus for the analysis of condensation phenomena, one has to face some challenges. First of all, the heat flux must be determined indirectly, by looking at the coolant side or at the wall temperatures. Beside the heat flux, an accurate evaluation of the heat transfer coefficient associated with the two-phase phenomena requires an accurate evaluation of the surface temperature. Experimental techniques that do not require the measurement of the wall temperature (e.g. the Wilson-Plot technique) could not be used here, being the main thermal resistance on the coolant side. In fact, the

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Nomenclature

A	area [m ²]	z_2	position (2.75 mm) along the orthogonal axes of the sample [m]
c_p	specific heat capacity [J kg ⁻¹ K ⁻¹]	Greek symbols	
D_h	hydraulic diameter [m]	Γ_L	mass flow rate in the film per unit width [kg m ⁻¹ s ⁻¹]
$\left(\frac{dp}{dz}\right)_F$	two-phase frictional pressure gradient [Pa m ⁻¹]	ΔT	temperature difference [K]
dT/dz	temperature gradient along the orthogonal axis of the sample [K m ⁻¹]	ΔT_{ml}	logarithmic mean temperature difference [K]
$\bar{e}$	average deviation = $\frac{1}{n_{\text{points}}} \sum_{i=1}^{n_{\text{points}}} e_i$ [%]	$\Delta\theta$	contact angle hysteresis [°]
e_i	percentage deviation of the i -th point = $\frac{HTC_{\text{CALC}} - HTC_{\text{EXP}}}{HTC_{\text{EXP}}} \cdot 100$ [%]	θ_{adv}	advancing contact angle [°]
g	gravity acceleration [m s ⁻²]	θ_{rec}	receding contact angle [°]
G	mass velocity [kg m ⁻² s ⁻¹]	λ	thermal conductivity [W m ⁻¹ K ⁻¹]
h	enthalpy [J kg ⁻¹]	μ	viscosity [Pa s]
H_{lv}	latent heat of vaporization [J kg ⁻¹]	ρ	density [kg m ⁻³]
HTC	heat transfer coefficient [W m ⁻² K ⁻¹]	σ_N	standard deviation = $\left\{ \frac{\sum (e_i - \bar{e})^2}{n_{\text{points}} - 1} \right\}^{0.5}$ [%]
k	thermal conductivity [W m ⁻¹ K ⁻¹]	τ_i	shear stress at the liquid-vapor interface [Pa]
L	length [m]	Subscripts	
$\dot{m}$	mass flow rate [kg s ⁻¹]	AVE	average
n_{points}	number of data points [/]	BC	boiling chamber
p_{SAT}	saturation pressure [bar]	CALC	calculated
q	heat flux [W m ⁻²]	EXP	experimental
Q	heat flow rate [W]	IN	inlet
Re_f	condensate film Reynolds number [/]	l	liquid
S	cross section area [m ²]	m	mean
T	temperature [K]	Nu	Nusselt theory
T'	specimen temperature at 1 mm from the surface [K]	OUT	outlet
T''	specimen temperature at 2.75 mm from the surface [K]	post-cond	post-condenser
u_A	type A uncertainty [%]	SAT	saturation
u_B	type B uncertainty [%]	SS	shear stress
u_c	combined standard uncertainty [%]	SUP	superficial
u_m	expanded uncertainty [%]	v	vapor
z_1	position (1 mm) along the orthogonal axes of the sample [m]		

determination of the condensation heat transfer coefficient starting from the direct measurement of the overall heat transfer coefficient and from the estimation of the coolant side heat transfer coefficient is affected by high experimental uncertainty when the leading resistance is on the coolant side. As an additional problem, the direct measurement of the surface temperature over a nano-engineered substrate, by soldering thermocouples over it, is not feasible, since this would locally modify the surface properties, leading to a modification of the condensation process.

From the scientific literature, it can be found that almost all the experimental setups designed for the measurement of heat transfer coefficient during condensation of pure or non-pure steam are characterized by three main parts: an evaporator, a condensing chamber and a cooling system [5–12]. Auxiliary devices can be introduced for complete vapor condensation, for condensate collection, for process visualization and for non-condensable gas introduction.

To the best of the authors' knowledge, two main techniques for heat transfer measurement during condensation on engineered surfaces can be found in the literature: one is based on the Fourier's law, with the evaluation of heat flux and surface temperature from the measurement of the temperature profile inside a cylindrical sample over which condensation occurs [5–8]; the other technique is based on an estimation of the single-phase convective (internal) heat transfer coefficient on the coolant side when condensation occurs outside tubes [10–12].

When evaluating the surface temperature through the Fourier's law, cylindrical metallic blocks (properly insulated to ensure one-dimensional heat conduction) are typically used and condensation takes place over one of the cylinder bases. These blocks are fitted with thermocouples in order to measure the temperature field, and thus to obtain the temperature of the surface over which the vapor condenses. To get a proper extrapolation of the surface temperature, several thermocouples are used and a minimum height of the block is required to allow thermocouples accommodation. Considering the extremely high heat fluxes expected during condensation, this technique leads to a significant temperature difference between the condensation side and the coolant side of the cylindrical sample. Therefore this method can be used only with metals having a high thermal conductivity, such as copper and aluminum, but it cannot be applied with metals or other materials displaying low thermal conductivity (e.g. stainless steel), unless entering with the cooling fluid at extremely low temperatures.

When performing steam condensation tests outside tubes, the main thermal resistance is located on the internal side, due to the much higher condensation heat transfer coefficient compared to the one in single-phase flow. This is even emphasized when dropwise condensation occurs over engineered-treated surfaces. Because of this, experimental techniques for the measurement of the external condensation heat transfer coefficient, based on the estimation of the internal single-phase heat transfer coefficient, may not be enough accurate. In fact, since the main part of the

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