



Review

Is dropwise condensation feasible? A review on surface modifications for continuous dropwise condensation and a profitability analysis



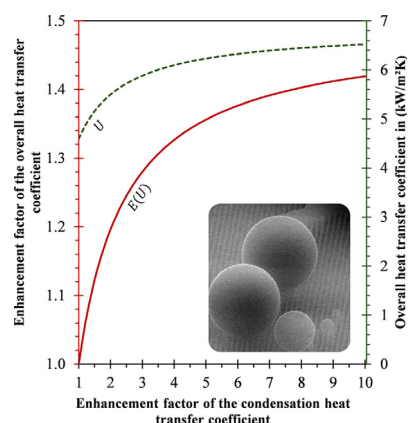
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HIGHLIGHTS

- Critical insight into the industrial application of dropwise condensation.
- Conclusive overview on the available and tested surface preparation techniques.
- Shortcomings and strengths of surface preparation techniques.
- Overview of the practical work on dropwise condensation in the past several decades.
- A case study providing a more realistic view on its feasibility and profitability.

GRAPHICAL ABSTRACT



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ABSTRACT

The interest in surface treatments promoting dropwise condensation has grown exponentially in the past decades. Savings in the operating and maintenance costs of steam processes involving phase changes are promised. Numerous surface preparation methods allow the formation of droplets during condensation. However, stable dropwise condensation has been hardly realized in industrial applications. This review aims to highlight the surface preparation techniques that promote dropwise condensation. It emphasizes on their durability and the resulting stability of dropwise condensation. Furthermore, the possibilities of implementation at an industrial level are discussed, apart from evaluating the economic feasibility through a case study. Despite years of research and numerous surface design possibilities, dropwise condensation cannot be maintained: coating deterioration and fluctuating process conditions commonly lead to surface flooding within hours or weeks. A more profound understanding of the mechanisms of dropwise condensation and innovative design concepts for self-renewing heat transfer surfaces may diminish encountered challenges.

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Introduction

The condensation of steam is a crucial aspect of many industrial fields. Consequently, it is of economic interest to make the conden-

sation process as efficient as possible to save on both investment and operating costs. Apart from the design of the heat exchanger and its material properties [1], its surface wettability has a significant impact on performance depending on the mode of condensation. Generally, several modes of condensation are possible, namely rivulet, film, and dropwise. Rivulets only occur when the heat transfer surface is not completely wetted, and will not be considered here. In contrast to conventional film condensation, the

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heat exchanger surface is covered by a condensate that is in the form of differently sized droplets during dropwise condensation. Dropwise condensation promises 4 to 28 times higher condensation heat transfer coefficients h_c than film condensation [2–5] and more than three-fold enhancement in the overall heat transfer coefficient U [2,4–6]. The increased heat transfer rate on surfaces with low wettability may be ascribed to (i) the reduction of thermal resistance caused by a condensate film, (ii) better liquid removal due to more rapid droplet shedding, and (iii) higher heat transfer rates through very small drops [7–9]. Most studies investigated the condensation of water vapor and commonly used heat transfer surface materials such as steels that are hydrophilic. Hence, it is common practice to decrease wettability through coatings, surface structures, or a combination thereof to promote dropwise condensation. Four functional surfaces are particularly promising in the context of dropwise condensation: (i) smooth hydrophobic surfaces, (ii) micro and nanostructured superhydrophobic surfaces, (iii) biphilic surfaces with patterned wettability, and (iv) lubricant-infused surfaces [10]. However, industrial implementation of such surface modifications is challenging. On the one hand, these surfaces are required to add no or negligibly small thermal resistances. On the other hand, their robustness and stability determine whether the wetting properties are maintained during continuous condensation. Depending on the industrial field of application, further aspects such as (i) toxicity, (ii) compatibility with the whole steam system in case of degradation, (iii) handling, and (iv) investment costs need to be considered [11]. Therefore, dropwise condensation is still mainly studied under laboratory conditions and is only rarely realized in industrial plants [12]. However, the development of new surface technologies and coating options has sparked industrial interest in dropwise condensation anew by offering the possibilities of cost reduction and increased heat transfer efficiency in times of increasing energy prices and dwindling resources.

Dropwise condensation can enhance almost all heat transfer processes that involve a phase change. The possible fields of application include seawater desalination [13–16] and thermal power generation [17,18]. There, steam condensers are among the most important components of the process and, hence, offer great potential for cost savings or enhanced efficiencies [5,16,19].

Seawater desalination plays an important role in the production of service and drinking water, especially in coastal, dry regions. Half of the expenses of a desalination plant involve the heat exchanger and the associated accessories [19]. The major technologies have improved continuously in the last 60 years [20]. Two main desalination techniques are in practice today, namely distillation and membrane processes. Reverse osmosis is the leading desalination technology, followed by thermal processes such as multistage flash and multi-effect distillation [13,16,20]. The thermal processes are based on the evaporation and condensation of seawater [13]. At around 50% of the total desalination capacity, such thermal desalination plants account for a considerable share of the global production of potable water [16]. Reports on the application of dropwise condensation in desalination plants are scarce, albeit several research groups have looked at its economic feasibility [14,21,22]. In 1966, the Franklin Institute in Philadelphia released a research and development progress report on the application of inorganic hydrophobic systems, mainly sulfides and selenides of copper and silver, and of vapor-deposited polymer films as promoters of dropwise condensation [21]. With regard to industrial implementation, steam was produced from purified water and saltwater. Additionally, the impact of cooling water velocity and non-condensable gases was examined. The report details the quality of dropwise condensation and its lifetime for several bulk materials and surface coatings and comments on the surface

changes observed. Enhancements in the overall heat transfer coefficient of up to 56% were achieved.

Condensers also play a major part in the operating cycle of thermal power generation plants. The steam generated by a heat source, i.e., nuclear fission or fuel combustion, drives a turbine via a temperature and pressure gradient, which produces electrical power in return. The steam liquefies in a condenser and then re-evaporates, following a closed loop. An improvement in the heat transfer occurring during condensation has a direct effect on its thermal efficiency and emissions [18]; dropwise condensation on a condenser surface accelerates the cooling and condensation of the steam. In this manner, it also increases the suction effect in the turbine by lowering its outlet pressure and temperature. A reduction of the condenser pressure from 67 mbar to 30 mbar can result in an efficiency increase of more than 2 percentage points [17]. In the mid twentieth century the optimization of marine steam propulsion installations was still of great economic interest and therefore was the subject of dropwise condensation experiments. For instance, tests were conducted in a marine condenser of S.S. Normania (British Transport Commission). Organic compounds promoting dropwise condensation were periodically injected into the steam so that they could chemically adhere onto the heat transfer surface and alter the wettability. Dropwise condensation was maintained for a minimum of two years [23]. However, the collected data was limited to visual evaluation of the formation of drops upon spraying with clean steam when the ship was in dock. No heat transfer measurements were taken [23], and the promoters were later found to be not suitable for the application [11]. In 1989, a condenser coated by a patented ion plating process was successfully installed in the Dalian power plant in China [15]. Overall heat transfer coefficients in the range of 6000–8000 W/m² K were recorded, as opposed to the commonly observed values of 2500–3500 W/m² K [24]. The number of condenser tubes could be reduced from 1600 to 800 [25], and the plant operated perfectly for a minimum of 4 years [15].

Cooling and refrigeration, heat pumps, and solvent recovery also include a condensation step. However, the working fluids are commonly different from water. There are only a few studies on the condensation of substances other than water [12]. Some researchers investigated the condensation of mercury, potassium, or ethanediol [10]. Yet, dropwise condensation of low surface tension fluids was investigated only recently [26,27]. For this reason, only the dropwise condensation of steam and its potential applications will be discussed in great detail in this review. The focus will be on heat transfer investigations on smooth and structured surfaces with gravity-induced droplet shedding, as they comprise the most established literature. Comprehensive studies of the relevant literature on biphilic [28–32] or lubricant-infused surfaces [26,27,33], enhanced droplet shedding by droplet jumping [34–36] or by a Laplace pressure gradient [29,37–39], and the influence of increased vapor velocities [38,40] are beyond the scope of this review.

The purpose of this review is to complement the available reviews on dropwise condensation by providing an overview on hydrophobizing techniques, with emphasis on their durability and the resulting stability of dropwise condensation. Furthermore, the possibilities of its implementation at an industrial level, as well as the economic viability will be discussed through a case study.

Optimization of heat transfer surfaces

Most heat exchangers are made of high surface energy materials such as aluminum, copper, titanium, or stainless steel, which promote film condensation through a phase change process [41]. To benefit from the merits of dropwise condensation, it is therefore

often necessary to alter the properties of the heat transfer surface. Hydrophobic coatings such as polymers may promote dropwise condensation. However, the maximum contact angle of water on smooth, chemically homogenous surfaces is about 120° , according to Young's theory [42–44]. In order to realize higher contact angles (and lower contact angle hysteresis) for faster droplet shedding, structuring of the surface is required [45]. It was shown that micro-scale roughness determines the contact angle, whereas nanoscale roughness has a major impact in decreasing the contact angle hysteresis, rendering the preparation of hierarchical structures desirable [46]. Such superhydrophobic surfaces can lead to phenomena such as droplet jumping, which allows the shedding of very small droplets even on horizontal plates [34,35]. The subsequent section will give an overview (see Fig. 1) on the different surface preparation techniques used to enhance the hydrophobic properties. It is followed by a literature survey on how these methods have been implemented in practice, including their cost estimates.

Surface preparation methods

A wide array of methods are available for changing the surface properties. Therefore, this chapter will focus on the techniques frequently used to prepare (super-) hydrophobic surfaces. The available techniques are often classified into top down (e.g., lithography, plasma treatment), bottom up (e.g., chemical deposition), or a combined approach (e.g., polymer solution casting, electrospinning) [47–49]. However, a clear distinction is not always possible and the classifications found in the literature differ from each other.

The top down approach generally involves structuring from larger to smaller length scales via, e.g., carving, molding, or machining of bulk material with tools and lasers [47,50]. Top down methods are primarily used to alter the surface topology at the nano and microscales. The bottom up approaches often involve self-assembly or self-organization [47]. Their great advantage over top down techniques is the molecular control of chemistry, composition, and thickness [47]. Often, bottom up methods are used to coat thin layers of hydrophobic materials on surfaces to decrease the wettability. However, they can also be used to fabricate surface structures. Combinations of top down and bottom up approaches are useful for producing two-scale hierarchical surface roughness.

In general, *lithography* is a method of transferring structural information from the master to a replica. The master can be either rigid, soft or simply a digital representation developed on a computer [51]. The master can also be produced by nonlithographic means. Micro and nanolithography can be subdivided into a variety of forms. A clear distinction between the subdivisions is not always possible as some of the methods used are a combination of several lithographic methods in order to realize increasingly higher geometrical resolutions [51]. The processing steps of the lithographic methods can differ greatly. There is, e.g., photolithography, which transfers a geometric pattern from a photomask to a photoresist on a substrate by using light. In the subsequent etching step, the uppermost layer of unprotected substrate can be removed. Furthermore, molding techniques such as nanoimprint or capillary force lithography produce negative replicas of the master through a heat, pressure, or light driven embossing process [47,52]. The master is then removed by lift off, dissolution, or sublimation [47]. A promising method used in wetting experiments is the so-called direct laser writing (also known as multiphoton lithography). It uses two-photon absorption to induce a change in the solubility of the resist, thus, it is capable of producing various 3D geometries [53,54]. Most lithographic methods are not suitable for large area applications as they require a clean room and expensive equipment [47,51].

Plasma treatment can change the surface chemistry and roughness of a material by bombarding it with the plasma species generated in a glow discharge, such as ions, atoms, or radicals [47]. Plasma treatment is commonly classified into plasma etching, sputtering, and polymerization [47,51]. Plasma etching is a dry etching method, by which material can be removed anisotropically; it is often used in the form of reactive ion etching or deep reactive ion etching (DRIE). The etch can be of physical or chemical nature, and is sometimes reported in the literature as physical and chemical sputtering [55,56]. Physical sputtering involves the removal of particles by collision, whereas chemical sputtering induces a chemical reaction that leads to the desorption of particles [55]. Change in both topography and surface chemistry can result from this method. To produce surface structures, different strategies are applied, such as the use of masks or the exploitation of the selectivity of source gases on material composition. Sputtering, on the other hand, can also be used to deposit thin films on a substrate by ejecting particles from a solid target material with the help of a plasma. It is one of the most promising methods in the

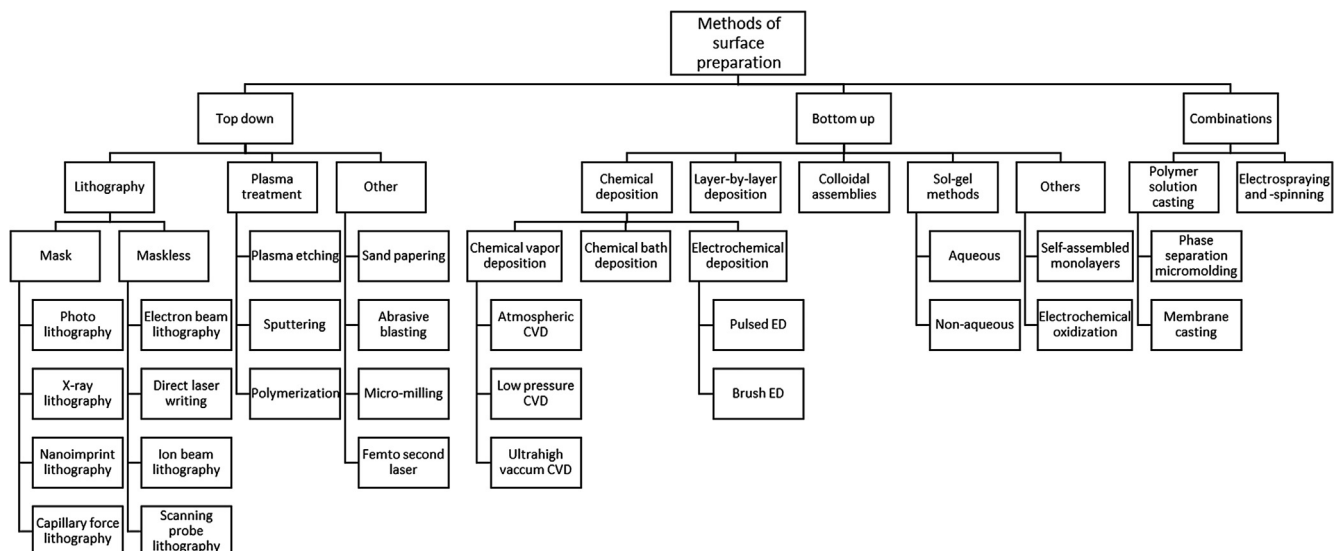


Fig. 1. Compilation of the surface treatment methods used for obtaining (super-) hydrophobic properties based on the classification attempts of several reviews [18,47–49,51,63].

field of physical vapor deposition (PVD), next only to evaporation and ion implantation [57]. It is also possible to alter the surface chemistry (and physics) by ion implantation [58]. When used in combination with plasma treatment, it is known as plasma-immersion ion implantation method [59]. Another method is plasma polymerization, which initiates polymerization via a gas discharge to fragment or activate a gaseous or liquid monomer. As a result of this process, a thin polymer film is deposited on a substrate surface [56]. The cost of production of plasma-treated surfaces varies depending on their complexity and the process environment. A nonvacuum process is more likely to be less time and energy consuming than a method involving the use of vacuum. An advantage of plasma treatments is the realization of a variety of interfacial properties without affecting the bulk properties of a material, which is contrary to what is observed in, e.g., temperature- and pressure-driven processes [56].

Other top down approaches include micromilling and micro-grinding [60,61], abrasive blasting [62], and femtosecond laser macromachining [63,64]. The latter is also known to produce hierarchical self-organized laser-induced periodic surface structures (LIPSS; [65,66]) or cone like protrusions (CLP; [67]), which are known to be hydrophobic.

Chemical deposition is commonly used to coat a substrate with thin films of crystalline inorganic materials [47]. Generally, it involves chemical reactions in which the product self-assembles and deposits on the substrate [47,51]. Several techniques are available, such as chemical vapor deposition (CVD), chemical bath deposition, and electrochemical deposition [68], also known as electroplating. In particular, CVD can be carried out in a variety of forms, such as thermally activated CVD, plasma enhanced CVD, or atomic layer deposition [69]. It is possible to classify the CVD process in terms of operating conditions as atmospheric pressure CVD (APCVD), low pressure CVD (LPCVD), or ultrahigh vacuum CVD.

Layer-by-layer (LbL) deposition is another thin film fabrication technique. In simple terms, this method involves multilayer buildup that is based on the assembly of oppositely electrically charged polyelectrolytes [70]. The deposition of a layer can be performed by alternate dipping of the substrate in aqueous solutions, by spraying, or by spin coating the solutions onto the substrate [71]. Thin films as well as rough layers can be produced by using this method [70]. To enhance the surface topology, nanoparticles can be incorporated into the solutions [47]. LbL deposition does not require a master or an environmental chamber, as is needed in the case of plasma treatment or CVD, and is, therefore, potentially economical [51].

Colloidal assemblies are formed when monodispersed particles link through chemical bonding or van der Waals forces [51]. Such particles, also denoted as colloidal objects, can have structural dimensions of the order of a few to a few hundred nanometers [50]. Their assemblies can form colloidal crystals, which can be further grown to hierarchical superstructures by directing the self-assembly process [50]. The methods for 3D colloidal assembly include, but are not limited to, electrodeposition, sedimentation, spray deposition, and spin-coating [50].

The *sol-gel method* is a wet-chemical technique used to prepare novel metal oxide nanoparticles as well as mixed oxide composites [72]. Films and colloids are usually produced by hydrolysis of an oxide in the presence of a solvent into a gel-like network and subsequent drying, which results in the formation of a relatively dense product [47,72]. Its definition, the transformation of a molecular precursor that proceeds through the formation of a sol and then a gel, has been handled loosely in the literature [73]. To be able to compare aqueous and nonaqueous sol-gel processes, Niederberger et al. denote a process as sol-gel as long as chemical condensation reactions are involved in the liquid-phase under mild conditions, leading to the production of oxidic compounds [73].

The sol-gel method is, e.g., used for the chemical solution deposition of electronic oxide films [74].

Other bottom up approaches include electrochemical oxidization or self-assembled monolayers (SAMs). Electrochemical oxidation, also known as anodization, is, e.g., used to produce porous anodic aluminum oxide [49], which can be employed as a template for embossing processes. A SAM results from the adsorption of an organic material on a substrate in the form of a one molecule thick layer. Often, a chemical 'head' group binds to the substrate, whereas the tail group exhibits the desired hydrophobicity [75,76]. The common methods to produce SAMs are silanization and thiolization [77].

Polymer solution casting is a manufacturing process that is employed in phase separation micromolding and membrane casting. It is a relatively easy method to produce rough surfaces during the film formation process [47]. Phase separation micromolding is a technique wherein a polymer solution is first casted on a master and then its thermodynamic equilibrium is disturbed. Contact with a nonsolvent or a change in temperature can trigger phase separation [78]. Membrane casting is a method used to produce porous structures. Initiated by nonsolvents or heat treatment, the polymer solution separates into polymer-rich and polymer-poor phases, which then form networks and pores, respectively [79].

Electrospraying and electrospinning are two related techniques. A high voltage is applied onto a polymer solution through an emitter (extrusion nozzle), resulting in the formation of a charged cone-jet geometry. If the jet dissociates into droplets, namely beads, the method is called electrospraying [80]. If the jet produces nanofibers, then electrospinning is the term used for the process [47,51,63].

Performance and durability of coatings

The coating and structuring methods presented have been widely used in wetting experiments. Usually, the wettability of a surface (and its surface treatment) is determined by measuring the contact and sliding angle of a deposited droplet. However, surface wettability may differ between deposited and condensed droplets [81,82]. Whether a claimed superhydrophobic surface is also suitable for dropwise condensation depends on the droplet-surface interaction occurring during the condensation and on the durability of the surface treatment. Fundamental research has attempted to describe the mechanisms of dropwise condensation, namely droplet nucleation [83,84], growth [36,85,86], and shedding [36,87]. Apart from experimental investigations, molecular dynamics simulations [88,89] and phase field simulations [90] appear to play a growing part in understanding the basic mechanisms of dropwise condensation. Other research groups pursued a more practical approach and investigated the heat transfer occurring during dropwise condensation with respect to its dependencies on the process parameters and the durability of the surface treatment. The latter shall be the focus of this chapter. In most cases, the surfaces of treated metal tubes (horizontal) or metal plates (vertical) were investigated. Table 1 shows an overview of the applied surface treatments reported in the literature for the investigation of heat transfer during dropwise condensation. For better comparability of the enhancement in the heat transfer, the coefficients of a modified heat transfer surface are related to those of an untreated heat transfer surface for the same subcooling, which is referred to as enhancement factor E [91]. The enhancement in the condensation heat transfer coefficient $E(h_c)$ is defined as the ratio of the condensation heat transfer coefficients h_c corresponding to dropwise and film condensations.

$$E(h_c) = \left(\frac{h_{DWC}}{h_{FC}} \right)_{\Delta T} \quad (1)$$

Table 1
Overview of applied surface treatments found in the literature for the investigation of dropwise condensation in steam. The coating thickness δ and the measured contact angle θ are indicated. Note that the underlying surface structure and the intrinsic surface material properties have a major influence on the droplet-surface interaction and the resulting dropwise condensation stability [107]. Similar surface alterations can be produced in various ways.

Method	Vacuum	Reference	Variation	δ [μm]	θ [$^\circ$]	Enhancement	Stability
Spray coating	No	Holden et al. [92] Kim et al. [93]	- TFE spray coating	60 n/a	n/a 95–97	$E(h_c) = 0.4$ (at 1000 mbar) $E(h_c) = n/a$ (at 1058–1127 mbar; 0.0015 kg/s)	>22,000 h >48 h
Dip- and spin coating	No	Ucar and Erbil [94]	Dip-coating	0.5–3	93–116	$E(h_c) = n/a$ (at ca. 1013 mbar; RH = 63%)	n/a
SAM	No	Das et al. [91]	-	0.001–0.0015	100	$E(h_c) = 9–14$ (at 1010 mbar); $E(h_c) = 4–5$ (at 83–103 mbar)	n/a
Sol-gel	No	Vemuri et al. [95]	-	n/a	148	$E(h_c) = 1.8–3.3$ (at 338 mbar)	>2600 h, decrease in θ and h_c
Ion implantation	Yes	Kamps [96]	-	1–20	108	Condensation performance increased by 30% (at 50 mbar)	>168 h, decrease in θ
PVD	Yes	Bani Kananeh et al. [99]	Plasma ion implantation	n/a	n/a	$E(h_c) = 2.2–3.2$ (at 1000–2000 mbar)	n/a
		Rausch et al. [100]	Plasma ion & ion beam implantation	n/a	n/a	$E(h_c) = 1.9–2.0$ (at 1200–1400 mbar)	>8 months
		Rausch et al. [101]	Plasma ion & ion beam implantation	n/a	70–80	$E(h_c) = 3.3–5.5$ (at 1050 mbar)	>670 h
CVD	Yes	Ma et al. [4]; Ma et al. [103]	Sputtering plus ion beam implantation	<0.1	96–114	$E(h_c) = 1.6–28.6$ (at 1013 mbar)	150 h to >1000 h
		Zhao and Burnside [15]	Ion plating	2–3	n/a	$E(h_c) = n/a$ (at 2000 mbar)	>4 years
Laser micro-structuring	Yes and No	Bonnar et al. [104]	rf PECVD	0.02–0.24	90–100	$E(h_c) = n/a$ (at 1013 mbar)	>7500 h
		McNeil et al. [105]	rf PECVD	1	n/a	$E(U) = 1.4$ (at 50 mbar; 9–34 m/s)	<336 h
		Koch et al. [106]	PECVD	2–4	65–90	$E(h_c) = 3.5–11$ (at 1000 mbar)	>500 h
		Faxson et al. [5]	iCVD	0.04	127–132	$E(h_c) = 7$ (at 1034 mbar)	>48 h
		Preston et al. [6]	LPCVD & APCVD	0.001	87 & 93	$E(h_c) = 4$ (at 1034 mbar)	>336 h
	No	Sharma et al. [38]	Subsequent wet etching	n/a	161	$E(h_c) = 7$ (at 1450 mbar, 3–9 m/s)	<9 h

Modifications of Eq. (1) may, e.g., include the ratio of the overall heat transfer coefficients U , where $E(U) = U_{DWC}/U_{FC}$.

Holden et al. investigated several spray- and brush-coated polymer and polymer-metal composite coatings in terms of their endurance and heat transfer performances. They were able to enhance the condensation heat transfer coefficient five- to ten-fold. However, most of the coatings showed only fair or poor long-term stability. Excellent long-term dropwise condensation (>22,000 h) was only achieved for one product. Unfortunately, the coating thickness of 60 μm posed much of a thermal resistance, therefore, despite dropwise condensation, the heat transfer could not be improved [92]. Kim et al. fluorinated transparent Pyrex glass tubes by spray coating to investigate dropwise condensation inside the tubes at atmospheric pressure for different steam flow rates. As the vapor quality inside the tubes decreased, so did the heat transfer rate. The durability was tested by measuring the contact angle of the fluorinated Pyrex tube after it was exposed to steam for 3 h for 3 consecutive days [93]. Ucar and Erbil dip coated different polymers on glass slides to evaluate the condensation rates on the surfaces. They found that the condensation rate decreased with increases in surface roughness, water contact angle, and contact angle hysteresis [94].

Layer thickness is less of a problem for SAM coatings, which are only a few nanometers thick. Das et al. tested SAM coatings on different metal tubes. Up to 14-fold enhancement in the condensation heat transfer coefficient at atmospheric pressure and up to five-fold enhancement in vacuum could be realized on SAM coated copper and copper-nickel alloy. The performance of the coating seemed to vary with the substrate material [91]. Vemuri et al. successfully tested a SAM coating prepared from n-octadecyl mercaptan solution on copper alloy for over 2600 h of continuous dropwise condensation. However, $E(h_c)$ decreased from approximately 3 (after 100 h) to 2 (after 2600 h). Prior to coating, the copper was polished and immersed in 30% hydrogen peroxide solution for 8 h to form an oxide layer for better bonding of the coating. Contact angles of up to 150° were measured, indicating the possibility of introduced surface roughness through the oxidization step [95].

A sol-gel system (tetraethylorthosilane, isopropyltriethoxysilane) was tested on horizontal aluminum and steel tubes by Kamps for its ability to maintain dropwise condensation and improve heat transfer. A 30% improvement in the condensation performance over untreated surfaces contrasted with the low coating durability of only 168 h [96].

In general, easy to apply methods such as dip and spin coating or spraying of SAM or sol-gel coatings are cost-effective, yet not very durable. Whether such coatings are applicable in the industry depends on the required maintenance effort and the capability of the concerned surfaces to refresh such promoters in operating heat exchangers. Furthermore, if heat transfer surfaces are modified prior to their mounting in the heat exchanger, damage of the coating is possible. To avoid this problem, Haje et al. came up with the concept of in situ coating of mounted heat transfer surfaces [97].

Vacuum-based coating processes, such as ion implantation and CVD, can produce highly adhesive and durable coatings with low thermal resistances, as evident from the following examples. Extensive research on ion-implanted surfaces for dropwise condensation has been conducted by Leipertz and Fröba [98]. As part of their research, Kananeh et al. modified stainless steel tubes through the plasma ion implantation process by using nitrogen ions. The condensation heat transfer coefficient could be improved by a factor of up to 3.2 [99]. Rausch et al. ion implanted aluminum alloys by using different techniques. An enhancement factor of about 2 was observed. The heat transfer coefficient was found to increase with increasing steam pressure and decrease with increasing surface subcooling. The stability of dropwise

condensation was maintained for 8 months. However, upon exposure to ambient air, the surface coating degraded severely due to oxidization [100]. In another work, they investigated titanium surfaces. Prior to ion implantation with nitrogen ions, Rausch et al. preoxidized titanium discs to stabilize the oxidation effects observed during steam condensation. The measured condensation heat transfer coefficient was found to be 5.5 times larger than that for film condensation. No significant change in heat transfer could be witnessed within the 650 h testing period [101]. The research group expected a roughness in the nanoscale to influence the form of condensation on ion-implanted metallic surfaces [102].

Through a combination of PVD and ion-beam implantation, Ma et al. sputtered an ultrathin layer of a polymer (PTFE) on several metallic substrates and simultaneously implanted the samples with nitrogen ions to improve the adhesion of the films with the metallic surfaces [4,103]. High enhancements (between 1.6 and 28.6) in the condensation heat transfer coefficient could be achieved. In their work, the substrate material seemed to affect the condensation heat transfer characteristics. Only one sample showed excellent dropwise condensation for over 1000 h in steam at 100 °C [4]. However, changes in the heat flux (variation of coolant temperature and pressure) lead to deterioration of the coating in a short period [103]. Zhao and Burnside reported a PVD technique, namely activated reactive evaporation-magnetron sputtering ion plating, to promote dropwise condensation. It was successfully tested at a power station in China and provided continuous dropwise condensation on brass tubes. At the time of publication, the coating had been maintained for four years. The overall thickness of the coating, composed of different sputtering ions (chromium, nitrogen) and Teflon, was around 2–3 µm.

CVD allows for a very thin promoter thickness and, hence, a negligible thermal resistance. Bonnar et al. investigated 16 different deposition conditions of hexamethyl-disiloxane (HMDSO) coatings on various flat metals and silicon substrates. The promoter was deposited by radio-frequency plasma-enhanced CVD. Life-test trials showed continuous dropwise condensation for over 7500 h on titanium and stainless steel. However, the HMDSO coating degraded on copper nickel alloy within 200 h [104]. Lab scale tests of such coatings under realistic turbine condenser conditions were later conducted by McNeil et al. [105]. Pure steam and an air-steam mixture (10,000 ppm air) were condensed on titanium tubes coated with 1 µm thick HMDSO at 50 mbar. The overall heat transfer could be enhanced by a factor of 1.4. Unfortunately, the coatings did not last as long in the more realistic process conditions and degraded in less than 2 weeks. Koch et al. coated copper with diamond-like carbon by using the plasma-enhanced CVD process. Enhancements of up to 11 times in the heat transfer coefficient of the measured film condensation could be obtained on a vertical wall. No instabilities of the promoter could be determined within the 500 h operational time [106]. Recent works of Paxson et al. and Preston et al. claim the development of durable coatings for continuous dropwise condensation. In an initiated CVD process, Paxson et al. grafted a thin layer (40 nm) of a polymer (PFDA-co-DVB) on aluminum. By immobilizing the polymer chains (through grafting and crosslinking), the contact angle hysteresis could be reduced. The relatively high contact angles of approximately 130° indicate some sort of crystallization during the process, leading to a higher surface roughness. The coating was tested through an accelerated endurance test at 103.4 kPa in 100 °C steam. A seven-fold enhancement compared to film condensation was observed. Within the 48 h testing period, the surface displayed no signs of degradation [5]. Preston et al. produced scalable single-layer graphene coatings by low pressure and atmospheric pressure CVD. The measured condensation heat transfer coefficient quadrupled in comparison to film condensation. In 100 °C steam, the coating showed no degradation within the testing period of over 2 weeks [6].

It should be noted that the majority of h_c used to describe $E(h_c)$ in Table 1 have been calculated via the experimentally determined overall heat transfer coefficient U by estimating the thermal resistances of the system. Furthermore, surface structures were neglected in the calculations. It is thus possible that (i) the calculation of h_c is flawed and that (ii) the surface area has been underestimated, accounting for a greater share in the increase in the heat transfer rate than what was considered.

Top down structuring methods are often found in the literature to have been used for studying the mechanisms of dropwise condensation. The method of choice is mostly a form of lithography with subsequent etching. As a result, uniform patterns with specific dimensions can be realized. However, this is only possible in relatively small dimensions, as it is limited by the processing chamber. Interestingly, these patterns often require an additional coating step to ensure sufficient water repellency. For example, after structuring a surface via oxygen plasma treatment, hydrophilic oxygen radicals may adhere to the surface. In a subsequent process step, the surface has to be treated with a hydrophobic material to ensure the desired droplet formation. Hence, it is difficult to assign a single surface preparation method to such surfaces. Sharma et al. are one of the few researchers to present hierarchically structured surfaces in accelerated heat transfer endurance tests. In the first step, they used laser microstructuring to produce arrays of truncated microcones on a copper sample (width = 78 µm, spacing = 81 µm, height = 50 µm, and opening angle = 26°) [38]. By employing a facile wet etching process, nanoscale features were added to the microstructure and the sample was subsequently coated with PFDT. The surface exhibited contact angles of over 160° and low hysteresis. Compared to plain hydrophilic nanostructured surfaces, an increase by a factor of 7 could be achieved for the condensation heat transfer coefficient. After 9 h of accelerated heat transfer endurance tests at 1.45 bar and steam velocities of 3 m/s and 9 m/s, the test surface showed the first signs of degradation, due to a loss of coating and nanotexture.

Table 2 shows some of the other combined methods reported in the literature. For hierarchically structured geometries, the micro and nanometer ranges are indicated. Naturally, such produced surfaces are neither cheap nor easy to produce.

Other surface treatments found in the literature include coating with noble metals, which showed stable dropwise condensation for over 10,000 h [112,113]. Whether the noble metals are hydrophobic or not has long been disputed. However, no clear answer has yet been found, as discussed elsewhere [114]. Another possibility of enhancing heat transfer through dropwise condensation involves biphilic surfaces, where hydrophilic spots aim to control the nucleation and the surrounding (super-) hydrophobic area enhances droplet shedding. Several research groups investigated such mechanisms on, e.g., surfaces with alternating surface structures [28–30] or hydrophobic/hydrophilic material composites [31,32]. Structured lubricant-infused surfaces have shown good repellency for non-polar liquids as well [27].

Regarding the durability of altered surfaces, several reviews exist, however, they may not necessarily be related to condensation [115–117].

Production cost of coatings

Developed structuring and coating methods allow various surface modifications that promote dropwise condensation and enhance heat transfer. However, many research groups focus on the wettability characteristics of the produced surface, while considering the complexity of the fabrication method as secondary or not considering it at all. The profitability of implementation in industrial heat exchangers, namely the production and maintenance costs, is seldom considered, albeit it is indispensable.

Table 2

Overview of the combined surface preparation methods found in the literature for the investigation of dropwise condensation.

Reference	Method	Micrometer range [μm]	Nanometer range [μm]
Chen et al. [108]; Boreyko and Chen [109]	Hierarchical square pillars: masking, DRIE, PECVD, SAM	width: 3.7–4.9 spacing: 11.2–12 height: 5.2–8.0	width: 0.06 spacing: 0.12 height: 0.4
Chen et al. [110]	Hierarchical square pyramids: photolithography, wet etching, DRIE, dip-coating	width: 14 spacing: 20–40 height: 12	diameter: 0.4 spacing: 0.2–0.4 height: 5
Cheng et al. [111]	Hierarchical square pillars: masking, DRIE, PECVD, SAM	width: 5 spacing: 9 height: 6	height: 0.4 25% surface coverage
Enright et al. [41]; Miljkovic et al. [86]	Hierarchical pillars: e-beam lithography, DRIE, SAM	diameter: 0.3 spacing: 2 height: 6.1	n/a

There are only a few reports on the fabrication costs of surface modification, let alone the maintenance effort required. A theoretical feasibility study was carried out by Diezel et al., which aimed to demonstrate the possibility of cost reduction of the seawater desalination process. Diezel et al. modeled the profitability of ion-implanted heat exchangers that promoted dropwise condensation in multivapor-compression (MVC) plants [22]. During the simulation, the increase in the heat transfer coefficient was estimated based on the enhancement factor $E(h)$ (see Eq. (1)). An enhancement factor of $E(h_c) = 5$ due to dropwise condensation and combinations thereof with increased evaporation heat transfer coefficients of $E(h_e) = 2$ and $E(h_e) = 5$ were modeled. According to their simulations, the capital and operating costs of a MVC plant could be significantly reduced, as shown in Fig. 2.

A few years later, the same group of authors published the results of more detailed simulations on the improved water unit production costs of an ion-implanted MVC plant with dropwise condensation [14]. Different simulation cases and process parameters were considered that led to a theoretical cost reduction of the product water of up to 35.4%. While such theoretical approaches combine all the areas affected by the enhanced heat transfer, they lack the experimental data for verifying the model assumptions.

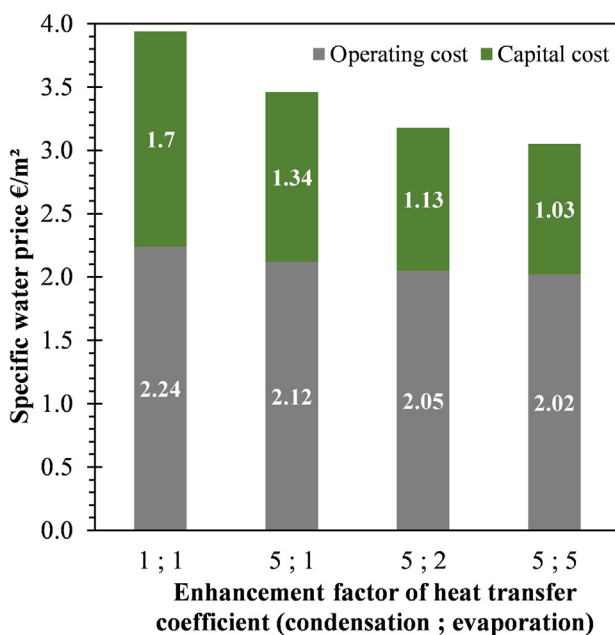


Fig. 2. Influence of ion implantation on the specific drinking water price of a 10 m³/d MVC plant. Adapted from [22]. Reprinted with permission, copyright John Wiley & Sons, Inc.

The following two research groups evaluated the production costs of their surface modifications, though they neglected the savings in the operational costs. Erb and Thelen investigated dropwise condensation on polymer- and noble-metal-coated copper as part of a research project at the Franklin Institute [21,113]. Although the total system cost of vapor-deposited ultrathin polymer coatings was estimated to be in the range \$0.15/ft² to \$0.20/ft² (approx. \$0.01/m² to \$0.02/m²), and hence economically very attractive, problems regarding the durability of the coatings were encountered. Electrodeposited noble metals were found to promote dropwise condensation far more reliably at a total system cost of \$0.70/ft² to \$2.12/ft² (approx. \$0.07/m² to \$0.20/m²).

Preston et al. developed scalable graphene coatings for enhanced condensation heat transfer by using CVD [6,118]. Including the electricity and gas consumptions for lab-scale production, their cost estimate added up to \$11.98/m² and \$57.95/m² for LPCVD and APCVD graphene coatings, respectively. However, process optimization and industrial scale fabrication were expected to reduce the costs significantly.

The examples for cost estimates agree in one aspect: they give an idea on the economic benefit of dropwise condensation in heat exchangers. However, the cost estimates are not conclusive. This is mostly attributed to the interdependent process parameters that make it difficult to calculate the cost accurately. While Diezel et al. chose to base their simulations on assumed improvement factors of the heat transfer coefficients [22], Erb and Thelen [113] and Preston et al. [6] included their own experimental data in the calculations. It should be kept in mind that the estimated enhancement factor of the overall heat transfer coefficient is strongly dependent on the process parameters of steam and the cooling side, as well as its material properties.

Feasibility study

The following chapter is aimed at (i) visualizing the effect of process parameters on the enhancement of the overall heat transfer coefficient and (ii) illustrating the economic benefits of dropwise condensation in a heat exchanger with regard to its overall performance and capital cost.

Theory

A conventional heat exchanger is a device that transfers thermal energy between two fluids that are separated by a conductive heat wall of surface area A and thickness δ . The combination of a series of conductive and convective barriers in a heat exchanger for transferring heat is described in terms of the overall heat transfer coefficient U or the total thermal resistance $1/UA$ [119]:

$$\frac{1}{UA} = \frac{1}{h_1 A_1} + \frac{\delta}{k_w A_m} + \frac{1}{h_2 A_2} \quad (2)$$

where k_w is the thermal conductivity of the wall and h_1 and h_2 are the convective heat transfer coefficients between the wall and the fluids. Note that h changes with, e.g., the flowrate and the temperature/pressure-dependent fluid properties. U varies with the reference area.

Assuming steady state conditions and negligible lateral heat transfer in the wall, the heat transfer rate \dot{Q} between two fluids in a heat exchanger depends on the overall heat transfer coefficient U and area A , as well as the logarithmic mean temperature difference between the fluids ΔT_{ln} :

$$\dot{Q} = U A \Delta T_{ln}. \quad (3)$$

From Eq. (3), it is evident that augmented U and A , as well as an increased temperature difference between the fluids, enhance the heat transfer rate similarly.

Modifications to the heat transfer surface for promoting dropwise condensation will initially increase the investment cost. On the other hand, an improved heat transfer performance can lower the energy expenses and reduce the heat transfer surface area required. A hydrophobic surface is also known to reduce the fouling and scaling rate in heat exchangers [120] and is likely to decrease the maintenance intervals. The total cost of a heat exchanger C_{tot} is a combination thereof. It consists of the capital cost C_C , the energy and material cost C_E , and other operating costs C_M (maintenance cost) [121]:

$$C_{tot} = C_C + C_E + C_M. \quad (4)$$

Savings in the energy cost are process-specific and difficult to generalize. Therefore, only C_C , namely the purchase price I_{HX} of a heat exchanger with size A , and its amortization factor a , and C_M are considered in this section. The maintenance cost is calculated as a fraction of the purchase price by multiplying with a factor s . Then, the total cost can be written as follows [121]:

$$C_{tot} = C_C + C_M = aI_{HX} + sI_{HX} = (a + s)I_{HX,0} \left(\frac{A}{A_0}\right)^{m_{HX}}. \quad (5)$$

The reference price $I_{HX,0}$ of a heat exchanger with surface area A_0 allows us to include the impact of the size of the heat exchanger on the apparatus cost. The value of the degression exponent m_{HX} is commonly less than 1 and depends on the specific equipment. Holland and Wilkinson recommended a value between 0.59 and 0.79, depending on the heat exchanger design [122]. The factor s varies between 0.01 and 0.02 for low fouling and corrosion risk, and increases to between 0.02 and 0.05 for planned maintenance and cleaning intervals and to between 0.05 and 0.10 for high maintenance requirements [123]. The amortization factor can be calculated according to [124]. The commonly found values are in the range 0.05 to 0.1 [125].

Case study

To put it in the words of Erb: *The reduction in capital cost by reducing the tubing and shell required must not be exceeded by the cost of materials and application of the coating system on the reduced surface area of the tubing* [126]. Hence, a balance has to be found between the additional cost of fabrication of the heat exchanger and the anticipated increase in performance to ensure price competitiveness. While it is known that dropwise condensation enhances the condensation heat transfer coefficient h_c in comparison to that observed in film condensation, its enhancement factor has to be seen in context with the other thermal resistances present in the heat transfer system. As is evident from the literature, (i) the enhancement factors vary strongly with the process parameters [2,3] and (ii) the enhancement of U is only a fraction of the enhancement of h_c [4,34]. The following section aims to examine

such relations by also considering the profitability of dropwise condensation.

Consider a water-cooled power plant where the process steam is condensed in a floating head shell heat exchanger with brass tubes. Water flows inside the tubes (subscript 1) and steam condenses on the outside (subscript 2). Table 3 lists the commonly found values for the (i) heat transfer coefficients of steam $h_{2,FC}$ (film condensation) and water coolant $h_{1,W}$, (ii) tube wall thickness δ , and (iii) conductivity of brass $k_{w,B}$ (taken from [127]).

Assuming a thin heat transfer wall, where $\delta/r \ll 1$, the heat transfer surface can be treated as a planar surface where $A = A_1 = A_2 = A_m$. Then, the overall heat transfer coefficient U of the given case, calculated by using Eq. (2), is $U = 4595 \text{ W/m}^2\text{K}$. In the case of an enhancement of $h_{2,C}$ due to dropwise condensation, the performance of the heat exchanger also improves. If, hypothetically, any increase of $h_{2,C}$ is caused by a change from film to dropwise condensation, the enhancement can be best described by the enhancement factor E . For $E(h_{2,C}) = 5$, the heat transfer coefficient is $h_{2,DWC} = 5 \cdot h_{2,FC} = 70000 \text{ W/m}^2\text{K}$ and U increases by a factor of $E(U) = 1.36$ to $U = 6232 \text{ W/m}^2\text{K}$. Of course, this holds true only if no additional thermal resistances are added to the heat exchanger surface that promote dropwise condensation, e.g., coatings. As depicted in Fig. 3a, an increase of $h_{2,C}$ does not affect U to the same degree: the influence of $h_{2,C}$ on $E(U)$ decreases with increasing $E(h_{2,C})$. For the case given in Table 3, the enhancement of U approaches about 49% when $E(h_{2,C}) \rightarrow \infty$ (Fig. 3a). To further optimize the heat transfer rate via U , the other thermal resistances have to be countered by either improving the thermal conductivity of the heat transfer surface or reducing the thermal resistance on the cooling water side (Fig. 3b). By improving either of them, $E(U)$ increases significantly, as $h_{2,C}$ accounts for a larger share of the total heat resistance.

Assuming constant heat flow rate and temperature difference of the fluids, the heat transfer surface area and U become inversely proportional to each other. Hence, a lower heat transfer surface area is required when U increases (Eq. (3)). According to Eq. (5), this affects the capital cost of the heat exchanger. Any surface modification to promote dropwise condensation is likely to increase the purchase price as a result of the higher production costs. Nonetheless, by taking into account the material savings and the lower maintenance requirements, the heat exchanger may become economical. For $m_{HX} = 0.59$ (from Ref. [122]), Fig. 4a depicts the relationship between the surface area and the resulting reduction in the capital cost while taking into account the different factors that contribute to additional production costs. Note that the total and capital cost ratios are the same if the changes in the factors s and a resulting from an enhanced heat transfer performance are neglected. A surface treatment that adds 10% cost to the original heat exchanger price will only become profitable if the increase in performance allows a reduction in the heat transfer surface area by 20%, relative to its original size. The surface area reductions required for lower investments are continuously growing with increasing surface treatment costs. The specified case (Table 3), for which the possible enhancement of U approaches about 49%, allows the surface area to be reduced to about 70% of its original size (Eq. (3); constant heat flow rate and temperature difference).

Table 3

Typical values for a heat exchanger, found in the literature [127].

Film condensation HTC $h_{2,FC}$	14,000 W/(m ² K)
Coolant HTC $h_{1,W}$	7,300 W/(m ² K)
Tube wall thickness δ	0.001 m
Conductivity of brass $k_{w,B}$	108.74 W/(mK)

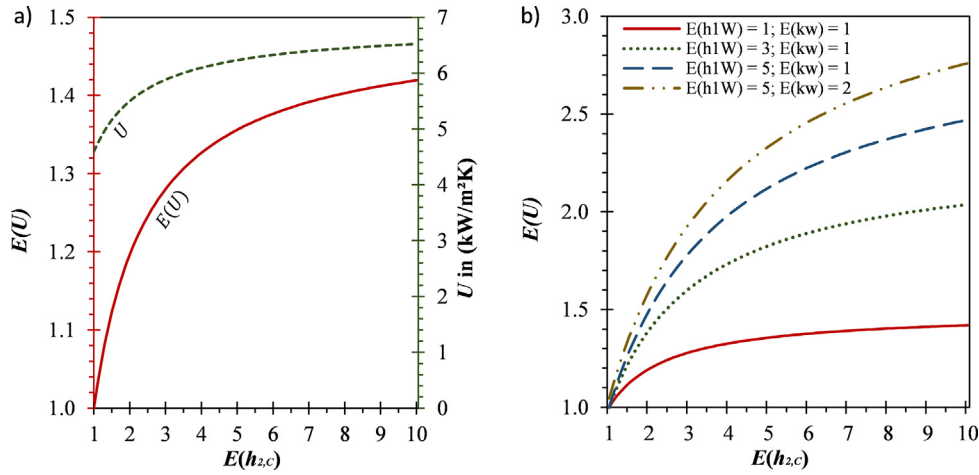


Fig. 3. (a) Influence of the enhancement of the condensation heat transfer coefficient on the overall heat transfer coefficient, compared to that observed in film condensation for the specified case (Table 3). $E(U)$ approaches a value of 1.49 for $E(h_{2,c}) \rightarrow \infty$. (b) Enhancement factor of the overall heat transfer coefficient U based on a combination of increased convective ($h_{1,W}, h_{2,c}$) and conductive ($k_{w,B}$) coefficients.

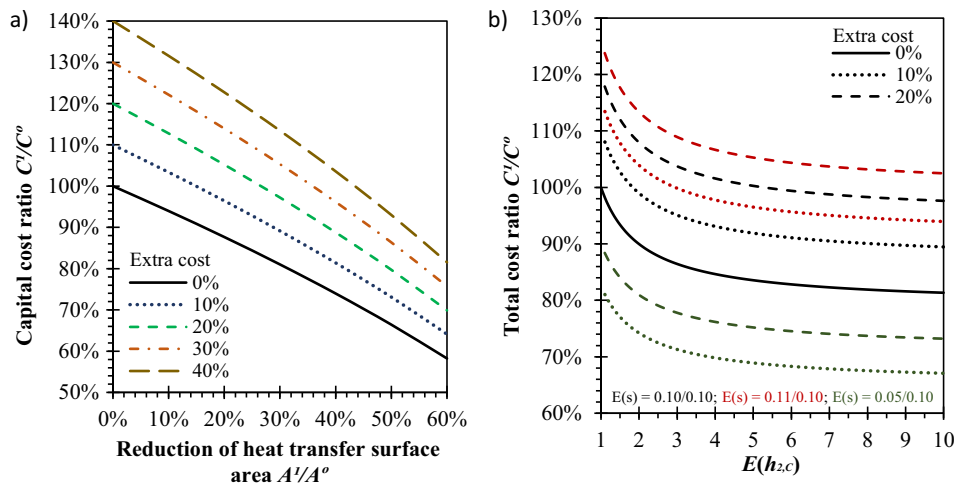


Fig. 4. (a) General relationship between the reduction in surface area and the resulting capital cost ratio of a surface-treated (superscript 1) to the original (superscript 0) heat exchanger for several additional production costs. (b) Influence of the condensation heat transfer coefficient on the total cost, considering different maintenance requirements (with $a = 0.1$). The graph is based on the specified heat exchanger (Table 3). It is first assumed that the maintenance requirements are high ($s = 0.1$) and not influenced by the surface modifications. For 10% additional cost, surface modification becomes profitable only for $E(h_{2,c}) > 1.9$. For 20% additional cost, surface modification becomes profitable only for $E(h_{2,c}) > 5.4$. Higher maintenance requirements ($s = 0.11$) due to, e.g., lower surface durability result in a performance increase of $E(h_{2,c}) > 3$ for 10% additional costs and no savings for 20% additional costs. Lower maintenance requirements ($s = 0.05$) due to, e.g., lower fouling propensity would result in savings for both 10% and 20% additional surface modification costs.

Hence, for any surface treatment costing more than 20% of the original purchase price, the capital cost cannot be outweighed any further.

This becomes even clearer in Fig. 4b. There, the influence of the condensation heat transfer coefficient $h_{2,c}$ on the total cost is shown. An enhancement $E(h_{2,c}) < 5$ has the largest impact on the capital cost. However, the additional costs owing to surface treatment to promote dropwise condensation quickly become uneconomical. Assuming a constant amortization factor $a = 0.1$ [125], a decrease in maintenance requirements (through, e.g., lower fouling propensity on the hydrophobic surfaces) results in the impact of additional production costs on the total costs being lower, and such a heat exchanger is economically viable. For higher maintenance requirements (low surface durability), the additional costs associated with surface treatment quickly become uneconomical. Enhancing $h_{1,W}$ or k_w/δ also has a positive effect on the size of the heat exchanger (compared in Fig. 3b). However, any enhancement in the coefficients entails a slew of other factors that need to

be taken into consideration, e.g., adjusting the water flow with additional pumps, which need to be purchased and lead to an increase in the energy costs.

The graphs presented can differ from case to case and the profitability of dropwise condensation should always be checked for the specific heat exchanger design and global process parameters. Indeed, dropwise condensation enhances the heat transfer coefficient h_c significantly. However, its share in the overall heat transfer coefficient may vary strongly. Several research groups reported disappointing heat transfer performances in field tests, despite continuous dropwise condensation, where, e.g., the added coating or coolant flow characteristics posed too high a thermal resistance to allow the increase in h_c to come into effect [19,128].

Conclusions

The phenomenon of dropwise condensation offers the possibility of increased efficiencies of many heat transfer processes. How-

ever, nine decades of research on dropwise condensation have still not produced a satisfying heat transfer surface design that allows its stable low-maintenance industrial application. This is mainly due to the fact that its fundamental mechanisms are not yet fully understood.

This review presents an overview of some of the industrial scale applications of dropwise condensation and the numerous laboratory-scale investigations that were attempted. The focus was on heat transfer studies of smooth and structured surfaces with gravity-induced droplet shedding.

The surface preparation methods primarily used to promote dropwise condensation are SAM, ion implantation, CVD, PVD, as well as dip and spin coating. The structuring methods include lithography and etching processes.

Whether the heat transfer enhancement achieved via surface modification is accompanied by a reduction in cost depends on various parameters. Critical to industrial-scale application are the production costs and durability of the surface treatment. Easy to apply coatings, such as dip-coated polymer layers, allow satisfactory droplet formation and shedding. However, they often require a thick layer for stability, which in turn increases the thermal resistance of the surface and negates the positive effects of dropwise condensation. In contrast, more elaborate processes that are often vacuum-based show good durability and low thermal resistances owing to very thin layers. Then again, such vacuum-based processes are more complex and expensive. The best durability has been demonstrated for ion-implanted surfaces.

In contrast to hydrophobic surfaces, there are no reports on the industrial applications of structured superhydrophobic surfaces that promote dropwise condensation. Whether the surface structures withstand the degradation occurring during continuous dropwise condensation remains unclear and should be investigated in future studies. In addition, their fouling inhibition is not fully evaluated and maintenance concepts for structured surfaces are lacking. Moreover, it seems that the projected area of the structured surfaces used to calculate the heat transfer may have led to overestimations of the heat transfer coefficients in some of the studies mentioned.

The contribution of the condensation heat transfer coefficient to the overall heat transfer coefficient varies strongly and depends on the material and process conditions, as determined by the case study. It is known that dropwise condensation enhances the condensation heat transfer coefficient; however, the profitability of dropwise condensation should always be checked for the specific heat exchanger design and global process parameters. Often, the material properties of the heat transfer surface or the thermal resistance on the coolant side constitute a more significant limiting factor. Reducing these thermal resistances first may enhance the heat transfer performance significantly. In addition, allowing the condensation heat transfer coefficient to have a greater share in the overall heat transfer coefficient will increase the impact of the condensation mode on the heat transfer performance.

Future perspective

As an interdisciplinary research topic, dropwise condensation combines the different aspects of thermodynamics and material science, where process parameters, droplet-surface interaction, abrasion, and oxidation go hand in hand. Regarding the fundamental understanding of dropwise condensation, standardization of the test conditions and the subsequent evaluation methods could simplify the comparison of differently prepared surfaces. In recent years, many researchers claimed to have developed a suitable heat transfer surface, though the majority failed to provide substantial data. It is often unclear whether dropwise condensation can be

maintained for a long period and for fluctuating process parameters. Emphasis on long-term experiments would give valuable data on the advantages and shortcomings of the proposed heat transfer surfaces. Only then can the endless design possibilities be narrowed down to a few choices that are worth optimizing. A better understanding of the droplet-surface interaction as a function of the surface material and process parameters based on more thorough experimental investigations would be the first step in the right direction. In particular, droplet nucleation lacks fundamental research, although it is known to play a role in determining whether a heat transfer surface is likely to flood or promote stable droplet formation. Furthermore, it remains a challenge to develop a durable and thin, yet inexpensive, large area coating and structuring technique. Innovative surface preparation methods, such as microscale 3D printing, offer new surface design possibilities. Much research effort is directed towards realizing higher structural resolutions on larger surface areas. The solution to surface deterioration may be bulk porous materials, such as Fluoropor [129]. They are insensitive to abrasion and show superhydrophobic characteristics. However, Fluoropor has not yet been evaluated in condensation experiments.

Conflict of interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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